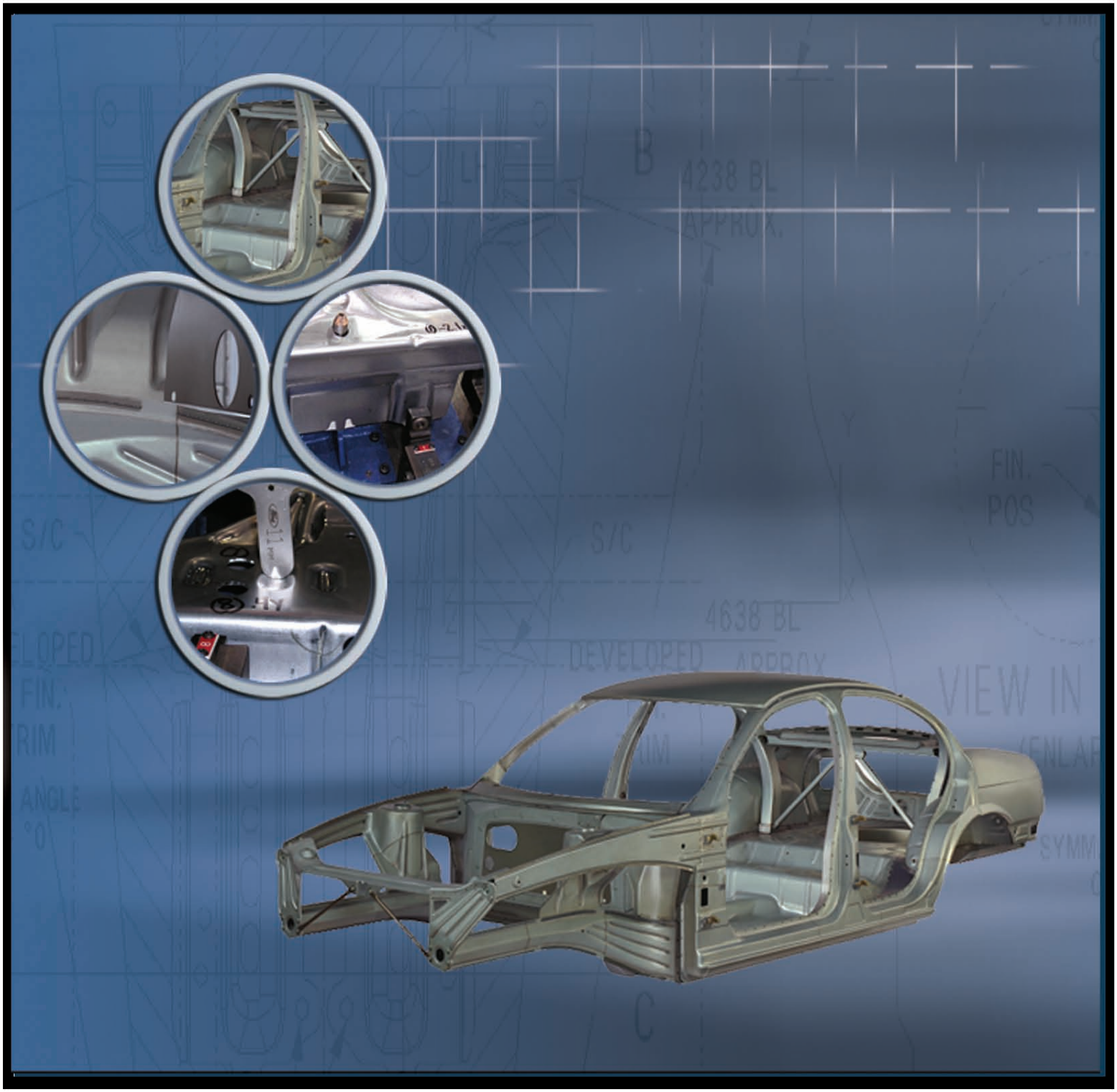

Advanced High-Strength Steel Applications

Design and Stamping Process Guidelines

A Special Edition of In-Depth AHSS Case Studies

Detailed case studies on the development and implementation of sheet metal stamping processes that employ AHSS steel grades.

Auto/Steel Partnership

www.a-sp.org (01/2010)

Advanced High-Strength Steel Applications
Design and Stamping Process Guidelines

A Special Edition of In-Depth
Advanced High-Strength Steel Case Studies

Auto/Steel Partnership
Southfield, Michigan
January 2010

The content of this book and future updates may be found
on the Auto/Steel Partnership (A/SP) website www.a-sp.org

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Preface

The AHSS Applications Guidelines Project Team of the Auto/Steel Partnership (A/SP) has conducted multiple in-depth case studies of advanced high-strength steel (AHSS) stampings for automotive structural components and has provided examples of these studies and lessons learned in this manual.

This manual of AHSS Application Guidelines is intended as an aid to automotive material engineers, product designers and stamping process planners when using AHSS for structural strength, safety and weight reduction of new vehicles. The information herein is primarily focused on two dual phase Steels, DP600 and DP800, due to the limited practical experience with the more advanced types such as DP1000, TRIP and Multi-Phase Steels.

Since the properties of AHSS can be tailored to suit specific application requirements, such as edge stretch, materials engineers and manufacturing engineers are advised to obtain property data from their steel supplier prior to selecting an appropriate material for a specific application.

This manual was compiled by the following members of the AHSS Applications Guidelines Project Team:

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The AHSS Applications Guidelines Project Team is composed of representatives from the A/SP member companies, as well as from the from the advisor and consultant companies listed below.

AK Steel Corporation
ArcelorMittal Dofasco
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AZ Automotive Corporation
Chrysler Group LLC
Ford Motor Company
General Motors Company
Nucor Corporation
Severstal North America Inc.
United States Steel Corporation

The Auto/Steel Partnership research communicates lessons learned from the case studies to product designers, stamping process planners and others involved in the production process.

The complete *Advanced High-Strength Steel - Design and Stamping Process Guidelines*, including the case studies, are available for download at www.a-sp.org.

This material is based upon work supported by the Department of Energy National Energy Technology Laboratory under Award Number DE-FC26-02OR22910.

Section 1

Advanced High-Strength Steel
Case Studies/Summaries

Case Study Summary #1

Part Name	REINF-CENTER/PLR OTR	**Material/Grade :**	DP340/590	**Thickness:**	2.0mm
Coating :	HD 60G60GU	**URL for Full Case Study:**	www.a-sp.org/publications.htm		

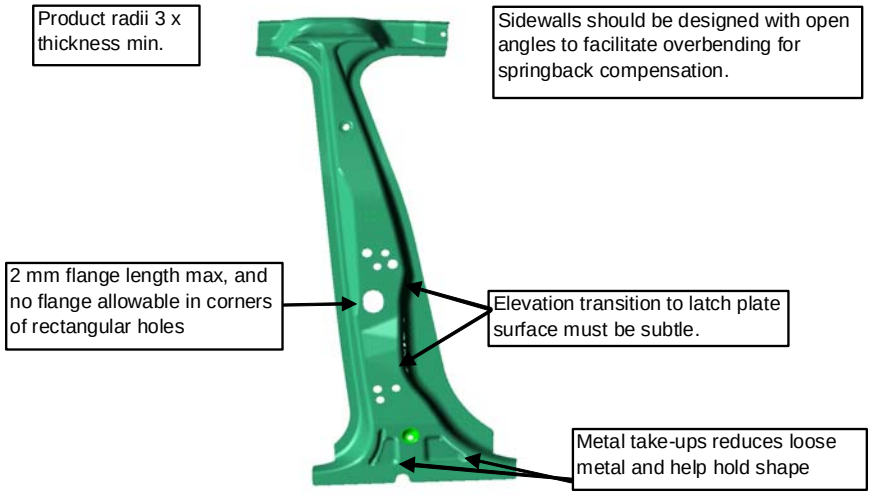
Spring-back/Twist Countermeasures: Development compensation / Binder restraint/Tighten radii in second form die.

Manufacturing Process

No. of Dies- 5	Draw	Pierce/Cam trim	Trim/Cam Trim	Cam Prc./Trim	Cam Lance		

Diagrams / Illustrations

Part Geometry



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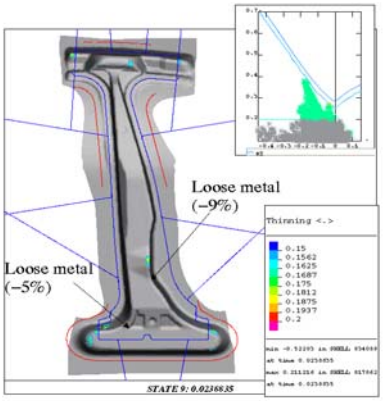


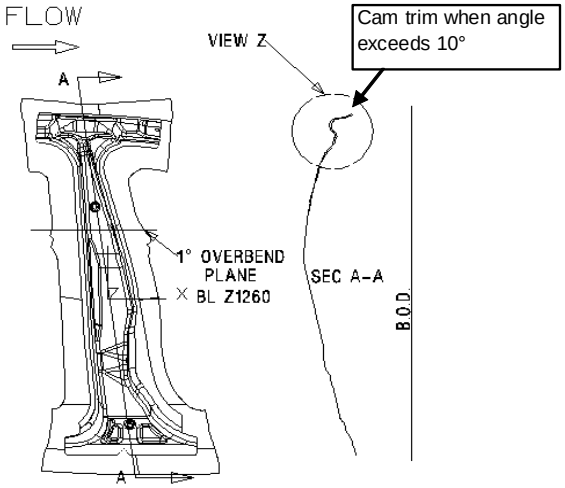
Die construction considerations

Binder tonnage requirements to set bead are 2 -3 times higher than mild steel

Coating form steels is required to prevent gaulling

Draw as much shape as possible in first form station

Draw radii requirement 10 mm



Notes

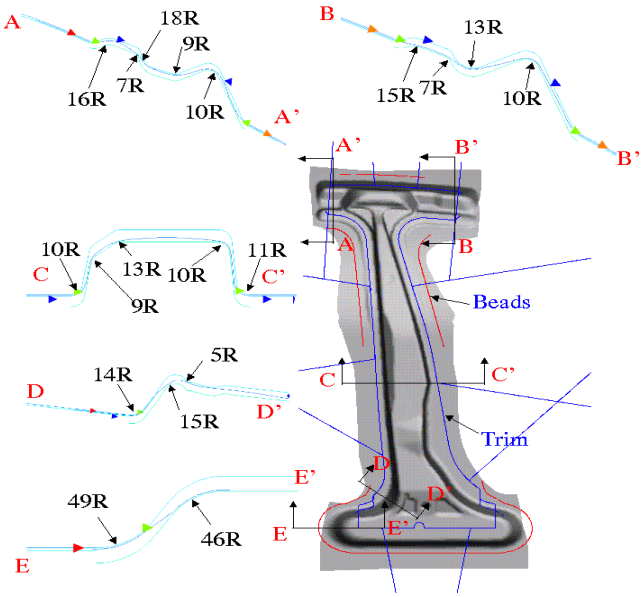
Bottom all form die pads

Coin radii to reduce spring-back

Tool compensation should be finalized with die trimmed panel

Section Information

Dimensional radii requirements for draw station



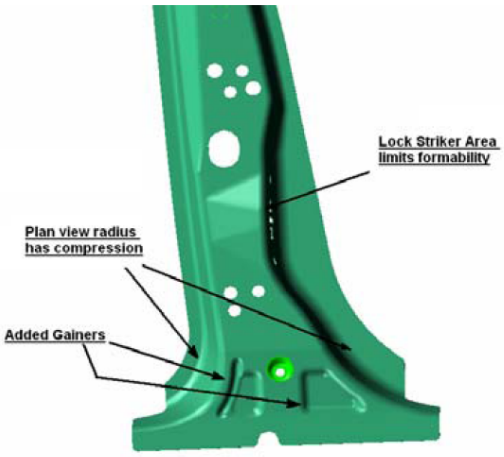
CASE STUDY #1:
REINF.- CENTER PILLAR OUTER

Gary Telleck
Global Stamping Architect
Advanced Vehicle Die & Stamping Engineer
General Motors Corporation
gm.com
gary.telleck@gm.com

PART DESCRIPTION

Part Name: REINF-CTR PLR OTR

Draw Depth: 80 mm

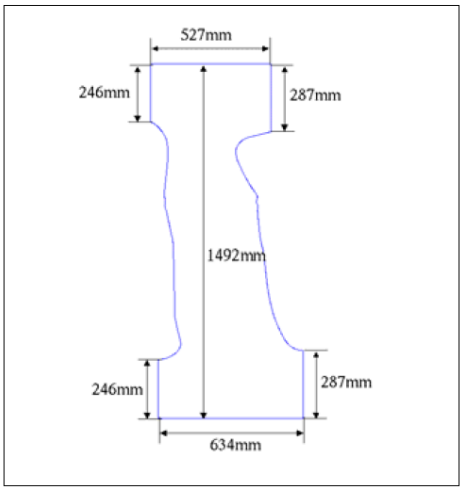


MATERIAL DESCRIPTION

Specification

Steel Grade:	DP 590
	CR 340Y/590T
Coating:	HD60G60GU
Gauge:	2.00 mm
Blank Width:	1492 mm
Blank Pitch:	1161 mm
Blank Shape:	Developed
Lubrication:	Blank Wash

Same Steel Vendor used for Try-Out & Production Material



PRESS LINE CONSTRAINTS

Press #1: B-Class – Tri-Axis Transfer Press
Lower Press Air Cushion

Current production rate = 13 SPM

Part or process factors that led to this press line assignment:

Part & Blank size
Lower press Air cushion for Air Draw

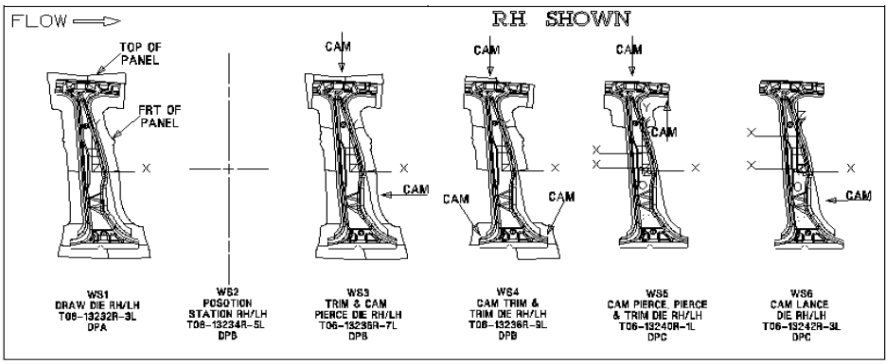
STAMPING PROCESS DESIGN

Process Overview

Forming Process Type: Draw Forming

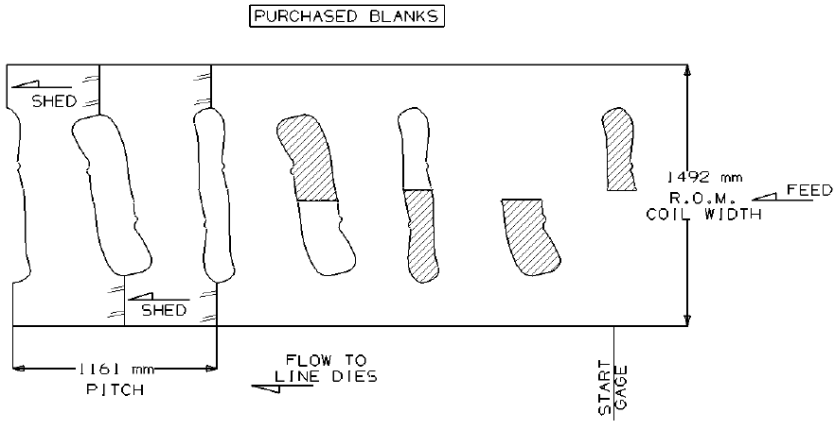
Process Flow:

Engineered Blank, Blk Wash → Forming operation → Position Station → Trim, CAM Pierce → CAM Trim, Trim → CAM Pierce Pierce, Trim → CAM Lance



STAMPING PROCESS DESIGN

Blanking Operation

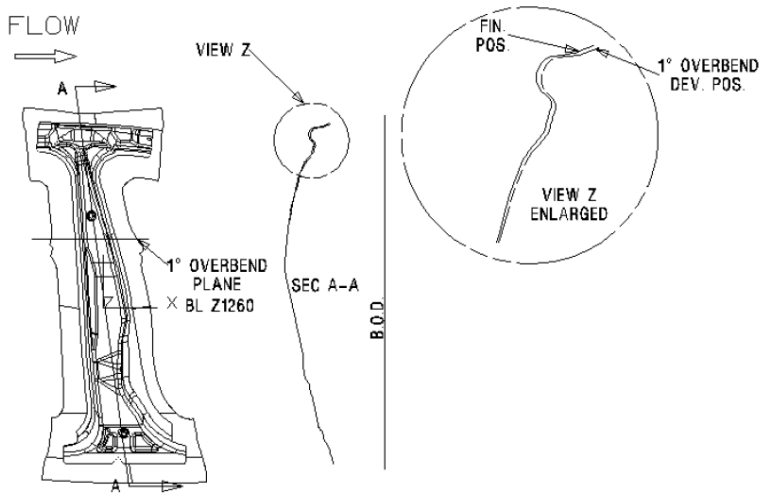


Include key parameters of blanking operation

- Trim angles
- Blade clearance
- Shear to break ratios
- Burr height
- Other sheared edge quality restrictions

STAMPING PROCESS DESIGN

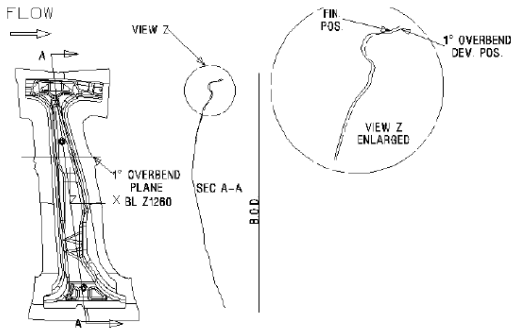
First Die Operation – Draw Die

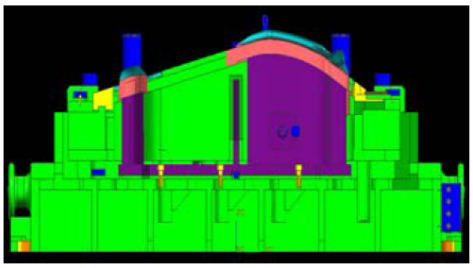


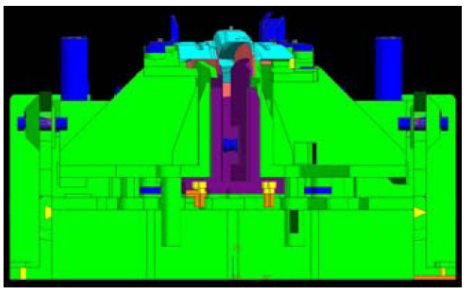
PARTS ARE SYMMETRICAL

STAMPING PROCESS DESIGN

First Die Operation – Air Draw Die



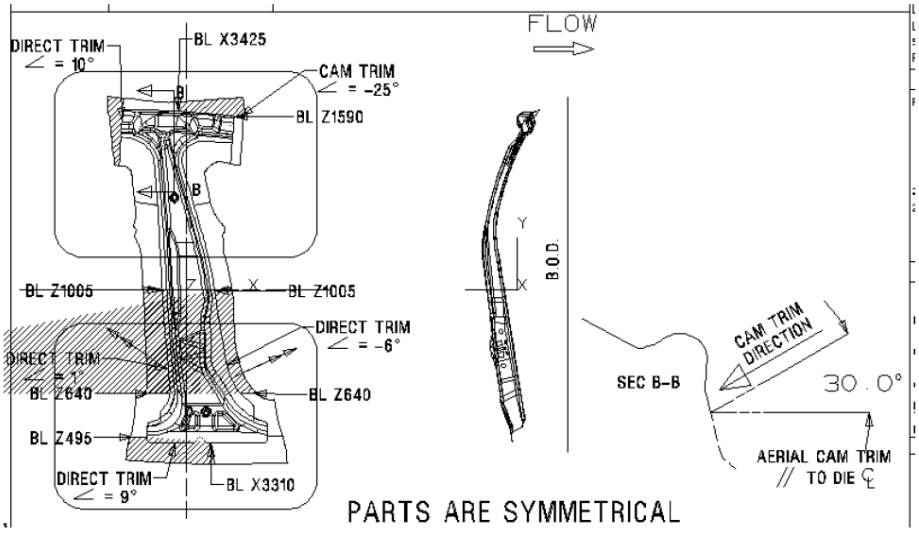




www.a-sp.org AHSS Applications Guidelines Project Case Study

STAMPING PROCESS DESIGN

Second Die Operation – Trim & CAM Pierce



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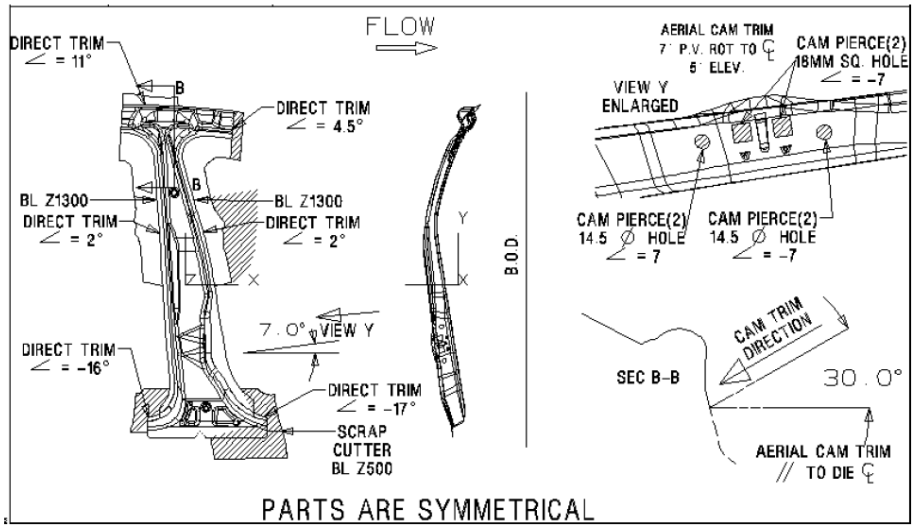
STAMPING PROCESS DESIGN

Third Die Operation – CAM Trim & Trim



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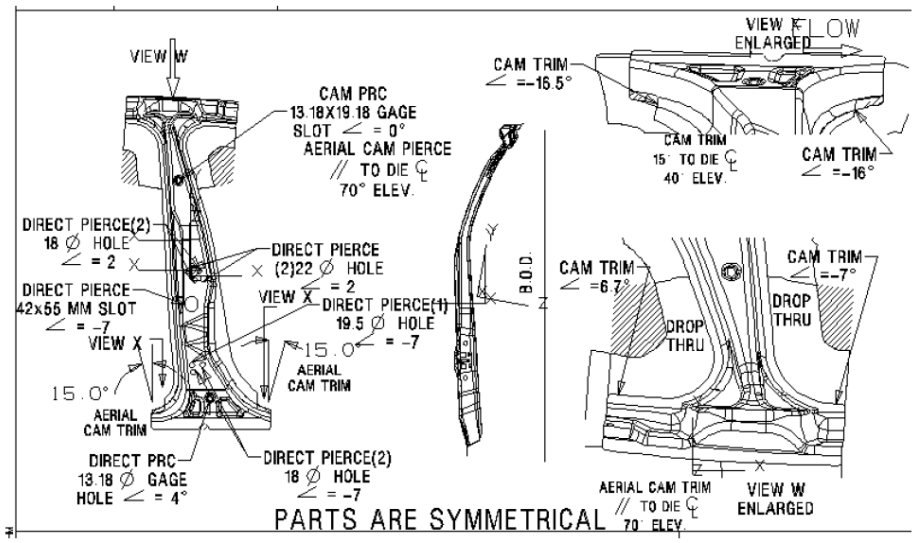
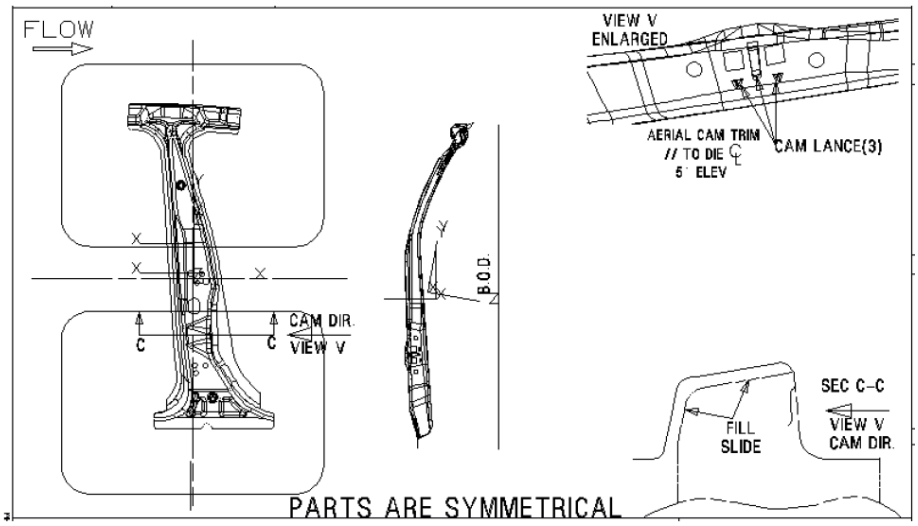
STAMPING PROCESS DESIGN

Fourth Die Operation – CAM Pierce, Pierce, & Trim



STAMPING PROCESS DESIGN

Fifth Die Operation – CAM Pierce, Pierce, & Lance

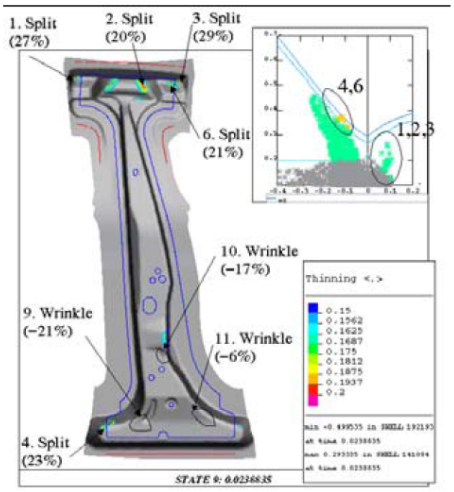


FEA FORMABILITY ANALYSIS

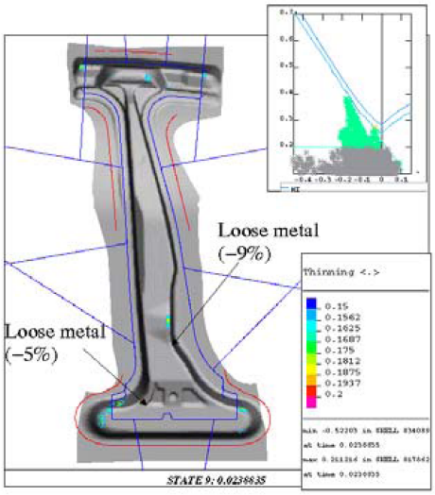
- PamStamp Analysis was used for Formability Simulation
  - Areas exhibiting high strain or thickening where corrected in product design
    - Critical Forming Radii are listed on following slides
    - Take up beads added in areas of thickening (see next slide)
- Worst Case Mechanical properties were used in analysis
- 0.1 Coefficient of friction used for analysis

FEA FORMABILITY ANALYSIS

First analysis results

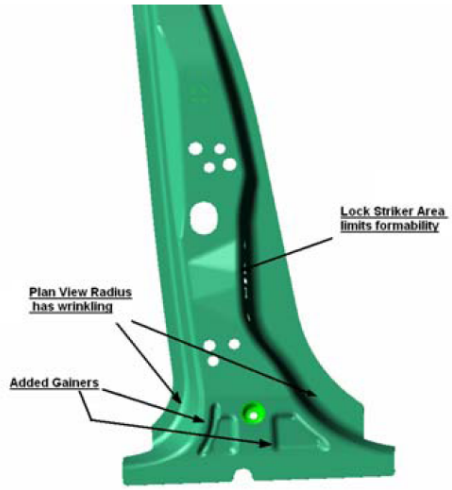


Final analysis results



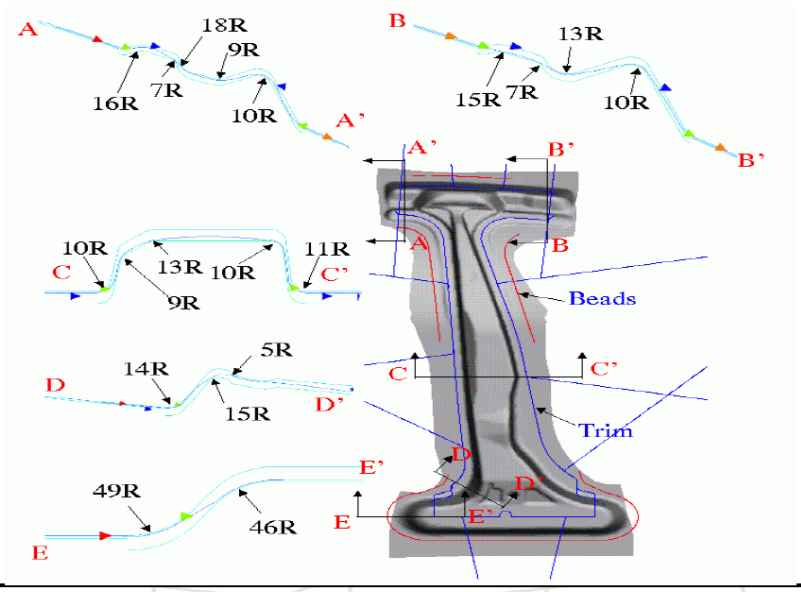
NEGOTIATED GEOMETRY CONCESSIONS

Geometry concessions needed to solve forming or springback problems that were accepted by Product Design



CRITICAL FORMING RADII

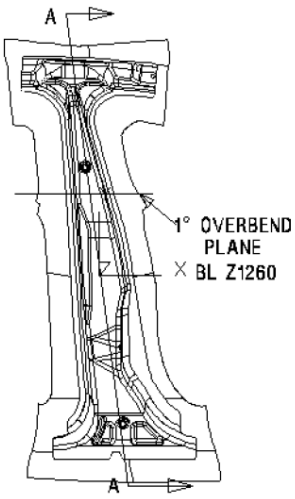
Dimensional radii requirements for draw station



SPRINGBACK COMPENSATION METHODOLOGY

1 degree over bend compensation used from a common neutral line

- **Amount of compensation was chosen based on experience**
- **Compensation was added to machine file prior to first die cut**



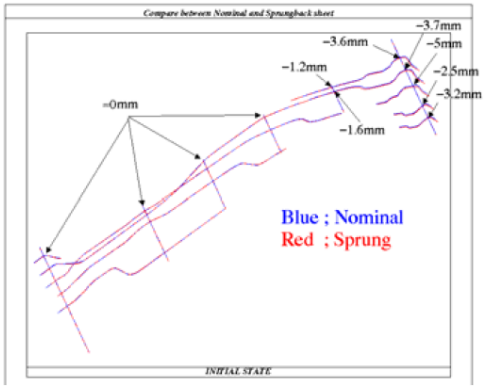
SPRINGBACK CONTROL HISTORY

- Die cut to compensation file with 1 degree over bend
- Springback found to be less than compensated
- Die Re-cut closer to nominal position after 1st tryout

SPRINGBACK MODEL ACCURACY

Results of Springback FEA

- Actual springback and predicted springback correlated well



PRESS LOAD PREDICTION ACCURACY

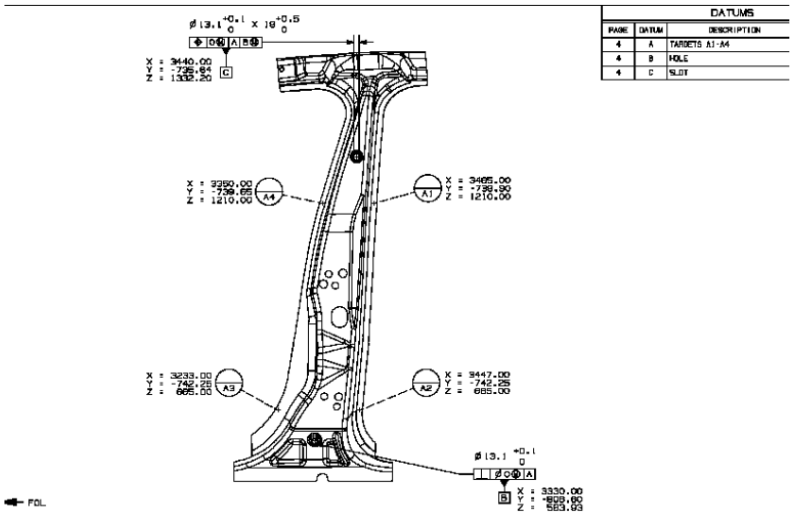
Die Stage	Press Loads (Tons)				
	Estimate	CAE Prediction	Actual Meas.	Total Available	%
Forming Press Binder	1297	1014 94	922 100	3000	
2nd Operation	151T				
3rd Operation	125T				
4th Operation	117T				

The method used for tonnage estimates was an engineering formula based on the bead length, punch opening & part feature length of line measurements. This calculation takes into account the material gauge and tensile strength and typically is higher than the formability estimate.

FIXTURING AND CLAMPING

Check fixtures and clamping methods

- Hard check tool used



POST-LAUNCH EXPERIENCE

Describe any insights gained during production

- Tool maintenance intervals - PM after 50K
- Heat buildup issues - Low based on 1600 / set up
- Tool wear rates - Wear on Lance Cam only
- Tool breakage problems – Trim steel chips only
- Part breakage/springback problems - None
- Dimensional stability and robustness - Stable
- Steel property variability effects – Tune in if supplier changes
- Die or process tweaks during production to solve problems
  - Better part gaging added to increase through put
  - Pre lube added to improve production robustness

- ** Production source has not had any Major issues to date after 1 year in production

LESSONS LEARNED

Overall Insights Gained – Product Design

- Nearly constant length of line in long part axis minimized springback.
  Consistent, heavy section resisted springback forces and minimized under-crown.

- Part should be designed open-ended to minimize forming problems.

- Product feature radii should be greater than 3x thickness with DP590, or 6.0 mm for this 2.0 mm thickness part.

- Sidewalls should be designed with open angles to facilitate overbending for springback compensation.
  Six degrees should be adequate for DP600.

LESSONS LEARNED

Overall Insights Gained – Draw Die

- Draw radii for 2.0 mm DP590 should be greater than 10 mm.

- Try to run draw die in its own press or slide to avoid ram tilt.
  Higher forming and binder forces required by AHSS can cause large asymmetrical press loads. If single press/slide, plan for nitrogen cylinders for balance.

- Higher DP600 strength required material upgrade (at least one grade higher) and more frequent maintenance for draw beads and die radii.

- Both hard check fixture and white light scanning are recommended.
  The greater springback encountered in AHSS may be too large for the fixture to accurately measure, but hard check fixture still needed for instant feedback.

- Pressures required to set draw beads and keep binders closed during draw are two to three times greater in DP590 than that for mild steel.

LESSONS LEARNED

Overall Insights Gained – Blanking, Trimming, Piercing Dies

- Higher DP590 strength required material upgrade (at least one grade up) for trim steels, dies, punches.
- Punches should be TiC coated.
- Urethane strippers should not be used with AHSS due to higher stripping loads and hold-down forces.
  Use hard stripper with mechanical or nitrogen spring.
- Piercings <5T should be 90 degrees to wall; piercings >5T should be 10 to 15 degrees degrees max. from vertical to wall.
- Springback should be read after actual trim die, not laser trimming, for accurate measurements.
  Trim dies and laser trimming produce different residual stresses and therefore different springback.

LESSONS LEARNED

Overall Insights Gained – Restrike Dies

- Do not rely on restrike to move previously work hardened material after the initial draw.
  Restrike can be used to coin radii or adjust angles, but it will not effectively change shape. Use restrike to add beads or darts to correct twist or crown or to add local feature embossments.

Case Study Summary #2

Part Name	Reinf. - Center Body Pillar	**Material/Grade :**	DP 340/590	**Thickness:**	1.65 mm
Coating :	HD 60G60G	**URL for Full Case Study:**	www.a-sp.org/publications.htm		

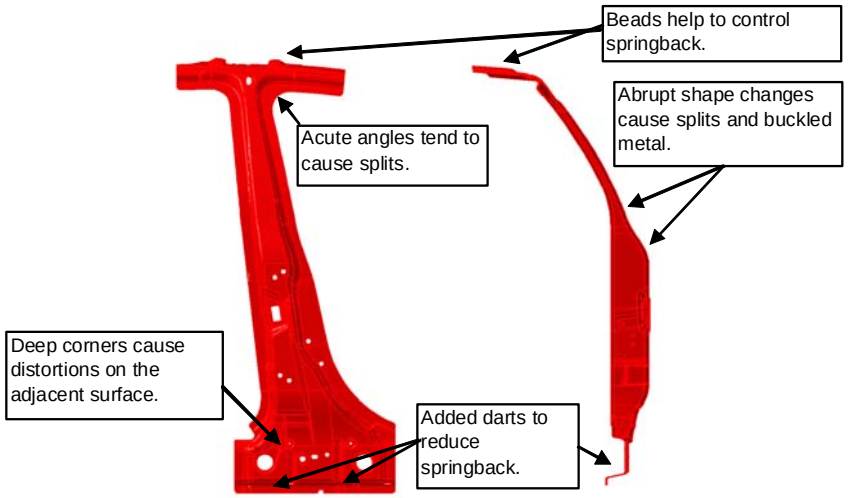
Spring-back/Twist Countermeasures: Draw bars and overcrown and twist compensationin draw die. Darts in restrike die.

Manufacturing Process

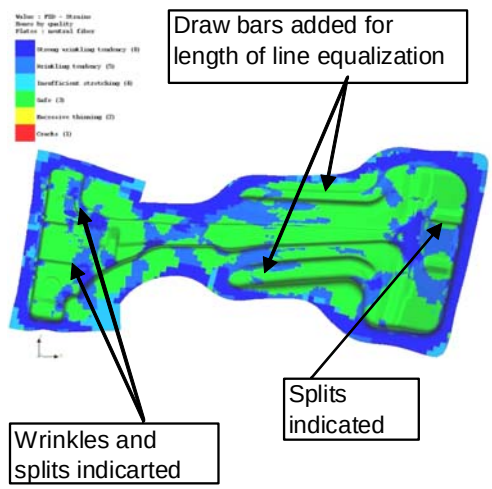
No. of Dies- 4	Draw die	Trim & Pierce	Tr.Prc.& Cam Prc	Form Trim & Restrike			

Diagrams / Illustrations

Part Geometry

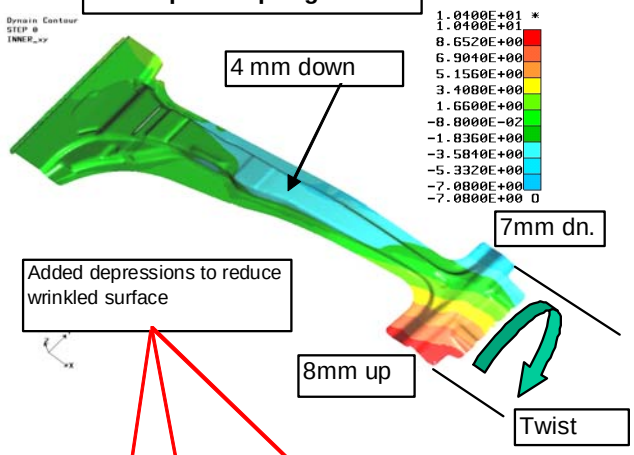


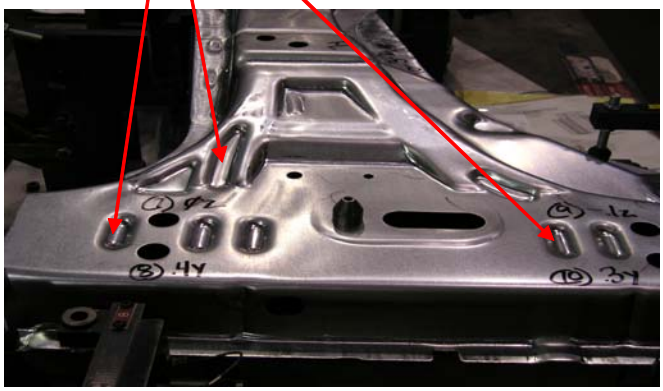
Formability Study



Die Construction Considerations

Computed Springback





Product Design Notes

Equalize length of line and depth of draw as much as possible in all cross sections.

Design channel sidewalls at least 6° open for DP590 springback

Abrupt surface transitions will cause splits and/or buckles.

Avoid acute corner angles and flanged holes.

3 x metal thickness is the minimum part radius for DP 590.

Die Construction and Tryout Information

Add compensation for springback, twist and camber to the first draw or form die as indicated by the forming simulation study. Recheck to a die trimmed panel.

Form as much of the finish shape as possible in the first die.

If possible, the first draw die should have its own press slide.

Binder pressures must be increased in proportion to material strength. Die construction must be more robust.

5 x T is the minimum die radius for DP 590.

Minimumize all trim & prc. angles. No acute angle trimming.

Bottom all form die pads.

Coin all flange break radii.

Upgrade materials for draw beads, trim and flange steels.

Design for higher thrust at flange steels.

Tryout -

Part tolerance expansions must be considered.

Functional build of sub-assemblies is a practical method of working with tolerance expansions.

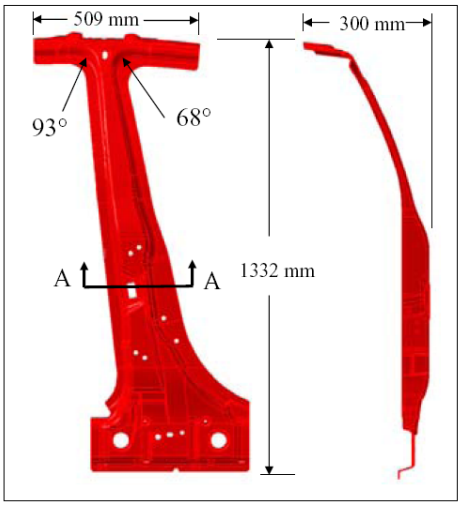
CASE STUDY #2:
REINF.- CENTER BODY PILLAR

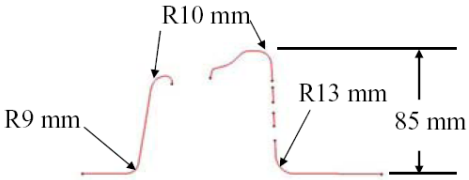
John Davis
VPE Manager
Ford Motor Company
JDavis7@ford.com

PART DESCRIPTION

Part Name: REINF- CENTER BDY PLR

Part size: is 509 mm x 1332 mm
- Part depth is 85 mm in section shown
- Critical Radii are shown in the section below
- Critical Plan View Radii are shown at the top of the panel.





Section A-A

PART DESCRIPTION

Part Name: REINF- CENTER BDY PLR

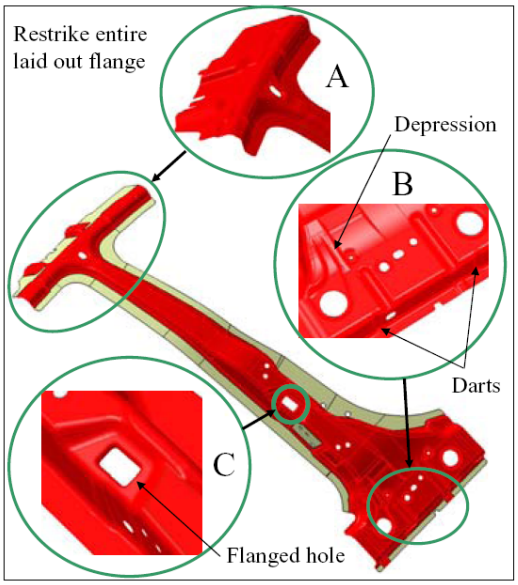
Mating surface features highlighted

Critical part features:

A) Top of part is flanged (laid out in draw)
Darts were added on the top flange to help compensate for springback.

B) Add depression to clean up wrinkles
Add darts to increase wall stiffness

C) Flange rectangular hole
(flange length is 2 mm)



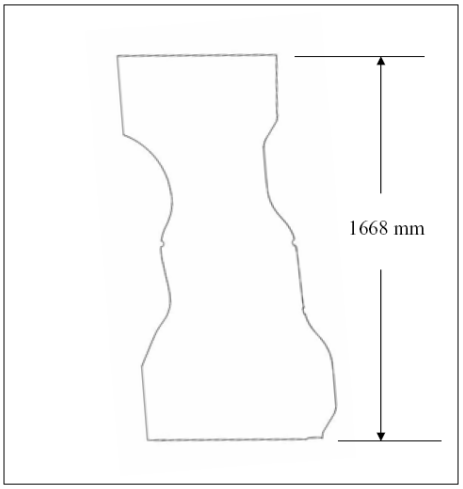
MATERIAL DESCRIPTION

Specifications

Steel Grade: DP600
Coating: Hot Dip 60G60G
Gauge: 1.65 mm
Blank Width: 1420 mm
Blank Pitch: 1668 mm
Blank Shape: Developed Blank
Lubrication: Mill Oil (1-2 g/m²)

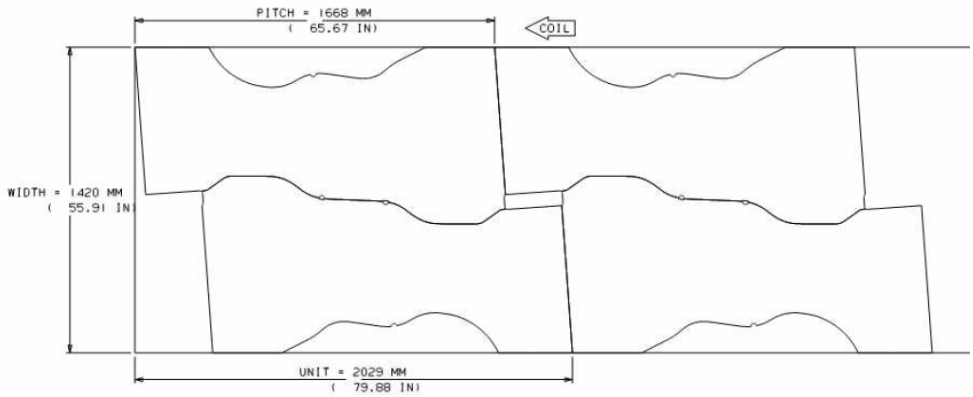
Material Properties (Try-Out)

Yield Strength: 359 MPa, 52 ksi
Tensile Strength: 627 Mpa, 91 ksi
Total Elongation: 25%
n-Value: 0.16 (strain range n.a.)



MATERIAL DESCRIPTION

Blank Nesting



PRESS LINE CONSTRAINTS

The part runs at Chicago Stamping Plant in Line 19.

Line 19 is a Transfer Press 288 X 108 Verson 3000T
Consists of 6 Stations
Tonnage = 3000
Die Station area Right to Left = 48 inches
Die Station area Front to Back = 48 inches

Target production rate is 450 / hour.

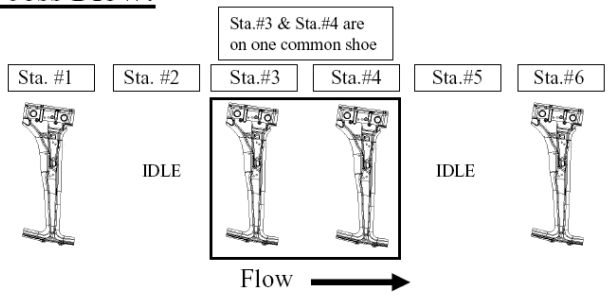
The press line was assigned after assessing the overall part depth and die sizes would not exceed the press requirements.

STAMPING PROCESS DESIGN

Process Overview

Station #1 Stretch Draw (Solid Upper)
Station #2 IDLE
Station #3 Direct Trim and Pierce
Station #4 Direct Trim, Pierce and Cam Pierce
Station #5 IDLE
Station #6 Form, Trim & Restrike

Process Flow:

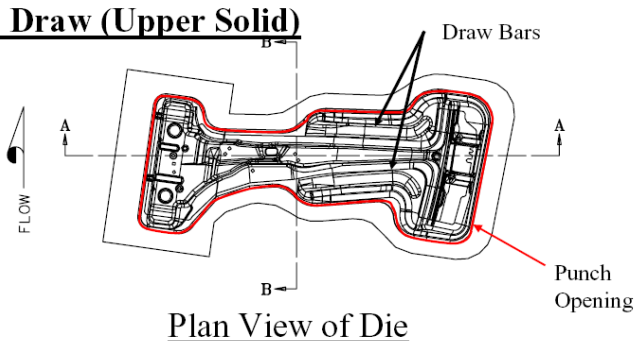


STAMPING PROCESS DESIGN

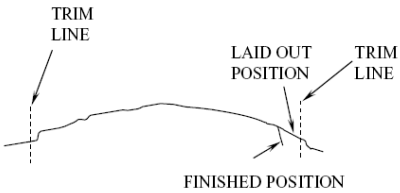
Station #1 - Stretch Draw (Upper Solid)

Draw complete except for laid out area at top of panel and upper portion of the front and rear door opening flange.

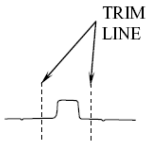
Draw bars added to help take up length of line condition at top of panel.



Plan View of Die

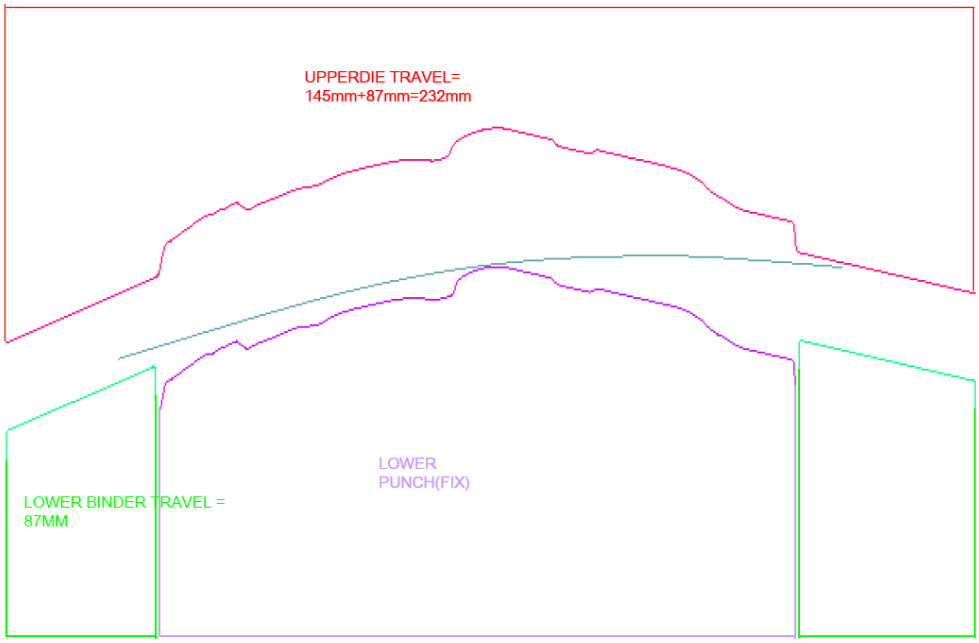


Section A-A



Section B-B

DRAW DIE SECTION



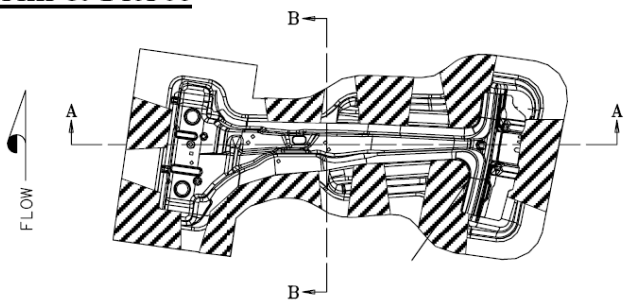
STAMPING PROCESS DESIGN

Station #2 - Direct Trim & Pierce

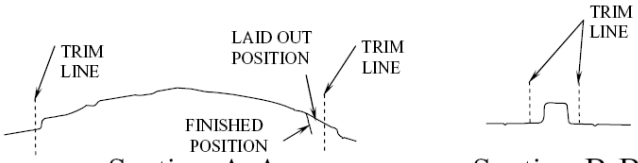
Direct Finish Trim and Pierce as shown:

Direct Pierce:

11 holes including Master Control hole and slot for locating part through dies.



Plan View of Die



Section A-A Section B-B

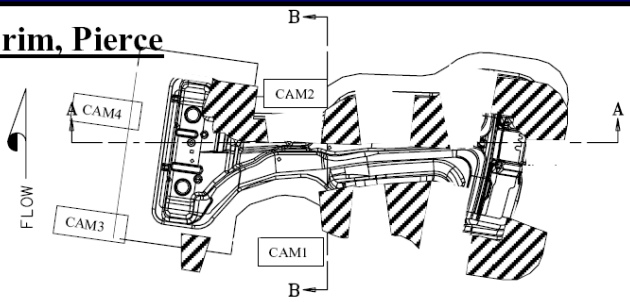
STAMPING PROCESS DESIGN

Station #3 - Direct Trim, Pierce and Cam Pierce

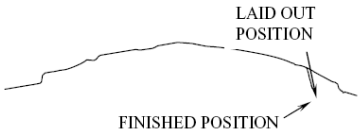
Locate Panel on M/C hole & slot.
Direct Finish Trim, Pierce and Cam Pierce as shown.
Cam 1 (Aerial)
Pierce 4 holes
Cam 2 (Aerial)
Pierce 4 holes
Cam 3 (Aerial)
Pierce 1 hole
Cam 4 (Aerial)
Pierce 1 hole

Direct Pierce (3) holes

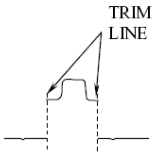
Finish Trim



Plan View of Die



Section A-A



Section B-B

STAMPING PROCESS DESIGN

Station #4 - Form, Trim and Restrike

Locate Panel on M/C hole and slot as shown.

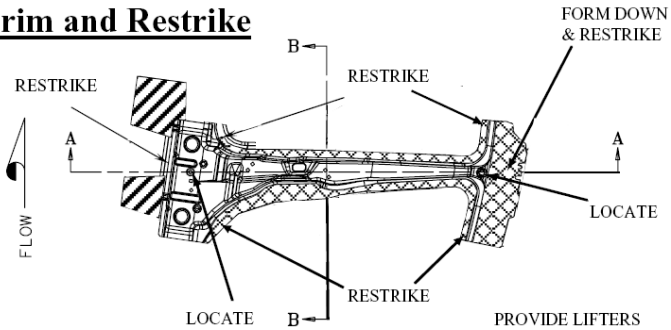
Finish Form and Restrike Top of panel.

Restrike Complete Front and Rear Door opening.

Restrike Lower part of Pillar

Trim off Remaining scrap

Flange 30.0 X 52.0 hole



Plan View of Die

Section A-A

Section B-B

FEA FORMABILITY ANALYSIS

The results of FEA formability study are shown on the next slides – predicted problem areas are shown in the circled areas, geometry concessions needed to eliminate the issues follow.

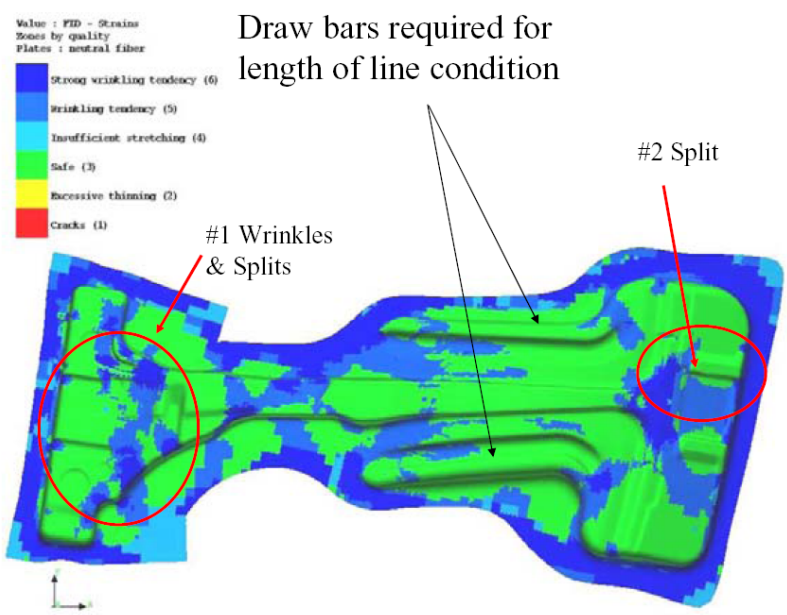
The mechanical properties used for the analysis were typical for DP600.

The friction coefficient used for analysis 0.12.

No shear failures were observed.

The CAE results correlated very well to the actual part.

FEA FORMABILITY ANALYSIS



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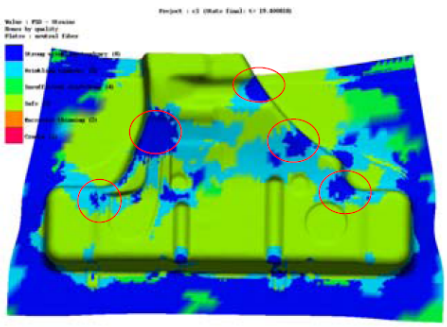
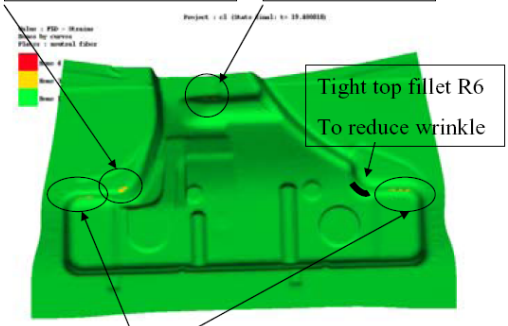
FEA FORMABILITY ANALYSIS

#1Wrinkles

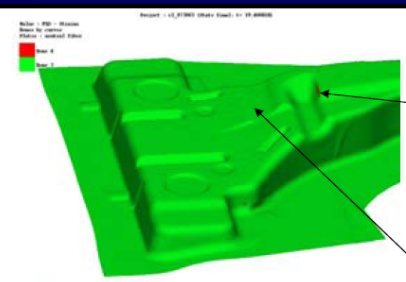
#1 Splits

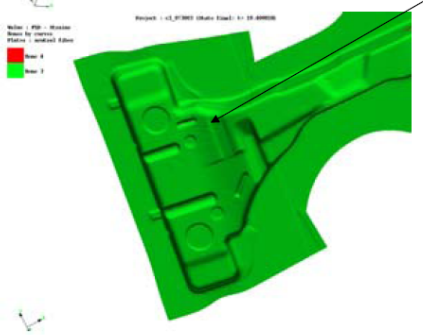




Material: *DP600, 0.9mm*

FEA FORMABILITY ANALYSIS

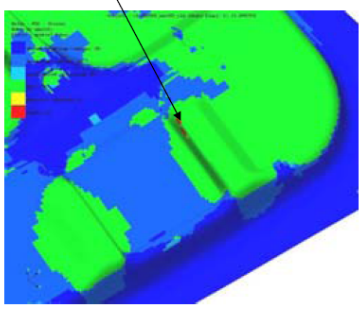




#1 Split

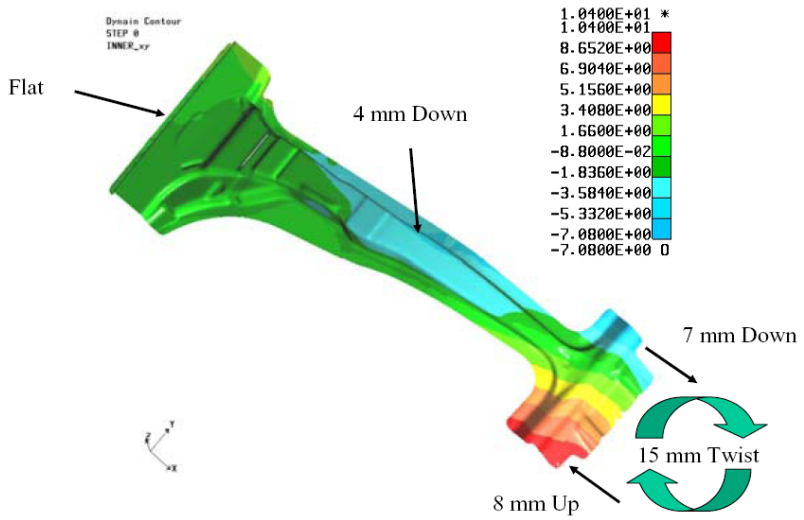
#1 Wrinkles

#2 Split



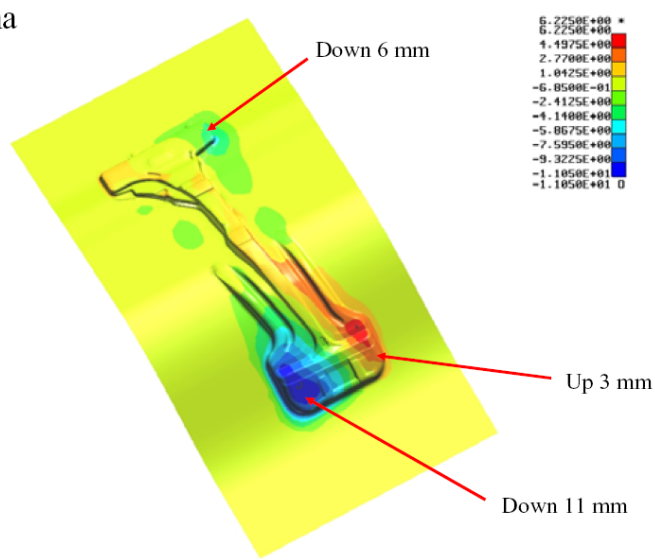
COMPUTED SPRINGBACK FOR B-PILLAR

The initial computed springback was calculated using OPTRIS and then LS-Dyna. The code type was explicit.



COMPUTED COMPENSATION FOR B-PILLAR

Springback compensation model is a Proprietary Ford add-on feature to LS-Dyna



NEGOTIATED GEOMETRY CONCESSIONS

The geometry concessions needed to solve forming or springback problems that were accepted by Product Design

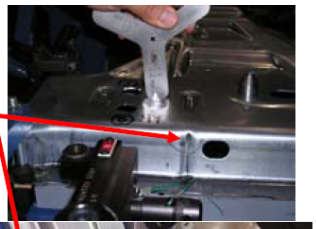
Included: Increased radii:

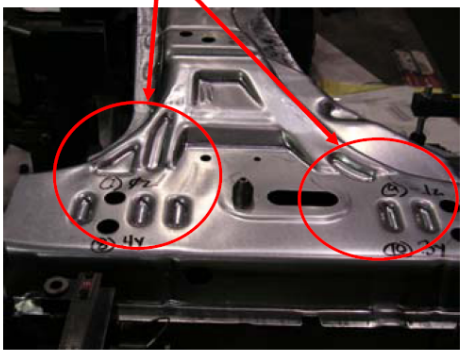
- To compensate for curl in the wall
- Enlarged fillets above striker section

NEGOTIATED GEOMETRY CONCESSIONS

The geometry concessions needed to solve forming or springback problems that were accepted by Product Design included:

- Added darts and beads to help hold part shape
- Added depressions to help take up wrinkles





SPRINGBACK COMPENSATION METHODOLOGY

The approach used to help control springback was to morph the draw die with the results from the springback study. The springback results were determined using a tailor welded blank (TWB) that contained DQSK material at the bottom of the panel and DP600 at the top of the panel. The new design changed after initial draw tryout. A tailor welded blank with DP600 at both the top and bottom at different gages was used to improve roof strength.

While the first tryout resulted in an acceptable drawn shell, the morphed draw die didn't include the effects of the restrike at the top and the overall results were not satisfactory. Furthermore, the design change to DP600 on the lower half was implemented without further compensation study. As a result, the draw die was recut twice.

The restrike die for flanging the top of the panel was recut twice. After making the proper springback moves using a fixture and measuring, the final work on the tools invovled sharpening the lower radius and coining with the top to hold the panels proper geometry.

PRESS LOAD PREDICTION ACCURACY

Die Stage	Press Loads (Tons)				
	Estimate	CAE Prediction	Actual Meas.	Total Available	%
Stretch Draw **Press Binder**	1000	800	1550		
Direct Trim & Prc	350				
Trim, Prc, C-Prc.	350				
Flg, Trim & Rstrk	500				

Actual tonnage measured under one ram (Total tonnage for line).

FIXTURING AND CLAMPING

Check fixtures and clamping methods

- A hard fixture was used for checking the part as shown below.
- Tolerance expansions were required to sell the part.

Example:

Upper flange springback

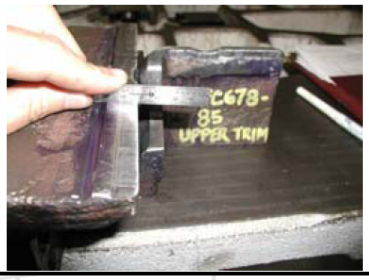
Was up to 8 mm away from the net and Level 3 points were over 3 mm high after clamping. It took two overbending moves in the flange die and then sharpening the lower radius and coining the top radii to bring the flange in tolerance.

POST-LAUNCH EXPERIENCE

Insights gained during production

- Premature wear on the draw beads after a 1000 parts.
  Substituted hard weld to correct the issue.
- Binder is scored and has microfractures
- Major Heat buildup in the draw die
- Tool breakage issues due mainly to improper die construction
- Ram tilt experienced during production
  Draw die & line dies are all under one ram. The large amount of tonnage required in the draw die caused the ram tilt. Added nitrogen cylinders to the final operation to balance out the ram.

•Flexing flange die.
Trim clearance was ok in static condition. Upper and lower trim steels strike when press is cycled. Picture shows 0.4 mm step worn into upper trim steel after 1500 hits. Caldie steels inserted in place of existing trim steels.



LESSONS LEARNED

Overall Insights Gained – Product Design

- Significant changes in length of line in long axis of part increase springback.
  Future parts should target more constant length of line from rocker to roof rail – heavier section in upper half will resist springback.

- Sidewalls should be designed with open angles to facilitate overbending for springback compensation. Six degrees should be adequate for DP600.

LESSONS LEARNED

Overall Insights Gained – Draw Die

- Major changes in material or die justify add'l Springback FEA.
  In this case, change from two-piece tailor welded blank with DQSK to monolithic DP600 blank proved to be major change. Repeating springback FEA after initial TWB die try-out should have minimized recuts to control springback.

- Try to run draw die in its own press to avoid Ram tilt.
  Higher forming and binder forces required by AHSS can cause large asymmetrical press loads.

- Higher DP600 strength required material upgrade (at least one grade) for draw beads.

- Both hard check fixture and white light scanning are recommended.
  The greater springback encountered in AHSS may be too large for the fixture to accurately measure, but hard check fixture still needed for instant feedback.

LESSONS LEARNED

Overall Insights Gained – Blanking, Trimming, Piercing Dies

- Higher DP600 strength required material upgrade (at least one grade up in shock resistance) for trim steels
- Higher loads with DP600 caused die flexing during flanging. Consider upgrading flange die standards to higher stiffness to minimize flexing under larger flanging thrust loads.
- Minimize piercing angles as much as possible.

LESSONS LEARNED

Overall Insights Gained – Restrike Dies

- Do not rely on restrike to move work-hardened material after the initial draw.
  Restrike can be used to coin radii or adjust angles, but it will not effectively change shape. Use restrike to add beads or darts to correct twist or crown or to add local feature embossments.

Case Study Summary #3

Part Name	Panel - Rear Rail	**Material/Grade :**	DP 350/600	**Thickness**	1.95 mm
Coating :	HD Galvanneal 40A40A	**URL for Full Case Study**:	www.a-sp.org/publications.htm		

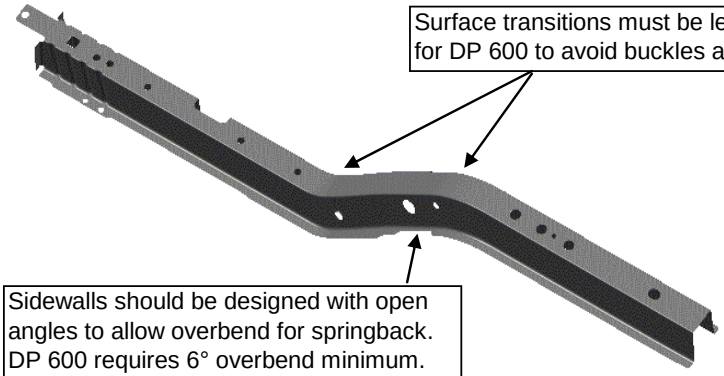
Spring-back/Twist Countermeasures: Cam Re-Strike Die added to correct springback and sidewall curl. (15° down angle)

Manufacturing Process

No. of Dies-	Dbl. Act. Draw	Trim and Pierce	Cam Re-Strike	Prc. Cam Prc.	Prc. Cam Prc. and Flg.		

Diagrams / Illustrations

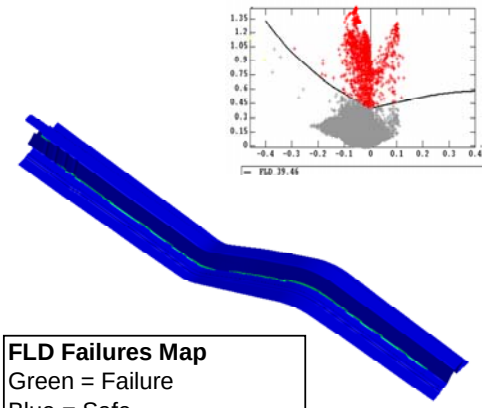
Part Geometry



Surface transitions must be less abrupt for DP 600 to avoid buckles and splits.

Sidewalls should be designed with open angles to allow overbend for springback. DP 600 requires 6° overbend minimum. Sidewall areas of metal compression may require more than 6° overbend.

FLD

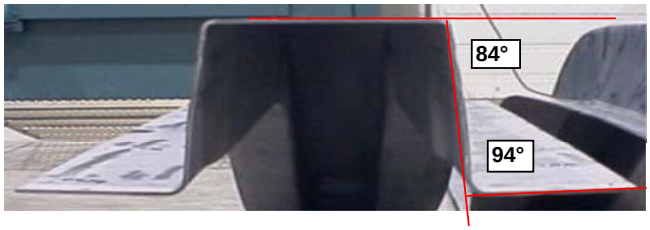


FLD Failures Map
Green = Failure
Blue = Safe
FLD Zero = 39.46%

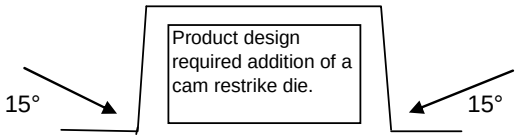
Die Process Considerations

DP 600 springback as compared to HSLA.
Product wall design is 3° open.

DP 600



HSLA



Cam Restrike Die - Cam Angles

Product Design Notes

Concessions needed to solve springback and forming issues:

- Hat section radius larger.
- Angle of beads at rear changed to suit draw die set-up.
- Sidewall springback tolerance was expanded.

Die Construction and Tryout Information

Draw die compensation should be finalized to a die trimmed panel.
A dbl.action press was used due to high binder pressure requirement
Draw die required an internal pressure pad to control buckles.
Bottom all form die pads.
Coin sidewall and weld flange radii to reduce springback.
Provide a robust die construction.
Upgrade all trim steels and tool steels subject to abrasive wear.
Trim as close to 90° to the surface as possible.
Expand tolerances where possible.
Use fuctional build approach for tolerance expansion.

CASE STUDY #3:
PANEL – REAR RAIL

Kerry Fitzgerald
AZ Automotive Corp.
AZautomotive.com
kfitzgerald@azautomotive.com

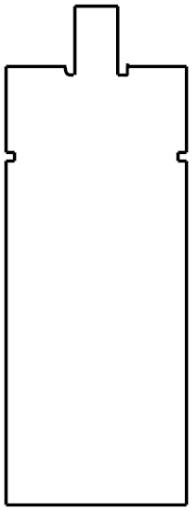
PART DESCRIPTION

Part Name: Panel – Rear Rail

- Mating surfaces and critical features:
  - -Flanges on both sides, some side wall areas. Waterfall area.
- Critical radii: Entire Hat Section
- Depth of draw: 4.25 inches
- Part features for dimensional stability:
  - -Ribs at one end

MATERIAL DESCRIPTION

Steel Grade:	DP 600
Coating:	HDGA
Gauge:	1.95 mm
Blank Width:	394 mm
Blank Pitch:	2351 mm
Blank Shape:	Rectangle with one end developed



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MATERIAL PROPERTIES

Mechanical Properties:

Mat'l:	DP 600
Mat'l Thickness:	1.95 mm
Yield:	379 MPa
Tensile:	622 MPa
n-value: (strain range 5 -15%)	0.148
r-value:	0.95

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PART HISTORY

NEGOTIATED GEOMETRY CONCESSIONS

Geometry concessions were needed to solve forming and springback issues:

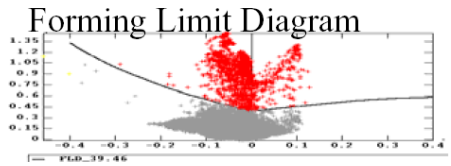
- Hat section radius
- Beads at one end
- Sidewall springback tolerance

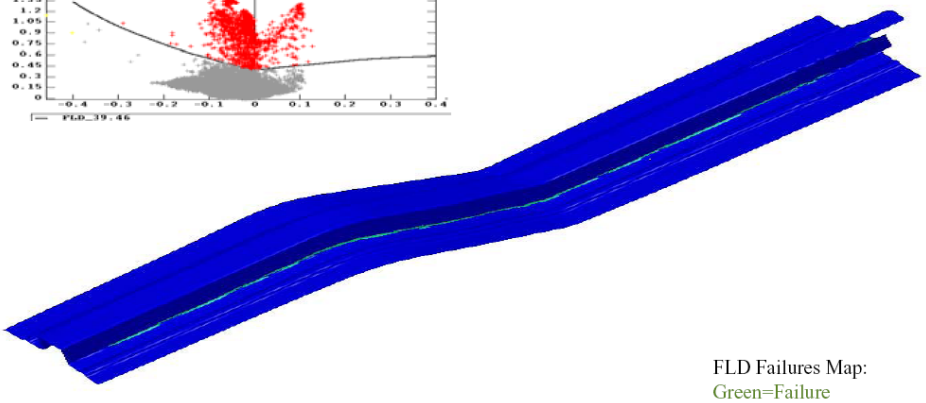
FEA FORMABILITY ANALYSIS

FEA FORMABILITY AN

FORMABILITY ANALYSIS

Forming Limit Diagram





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Green=Failure
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FLD Zero=39.46%

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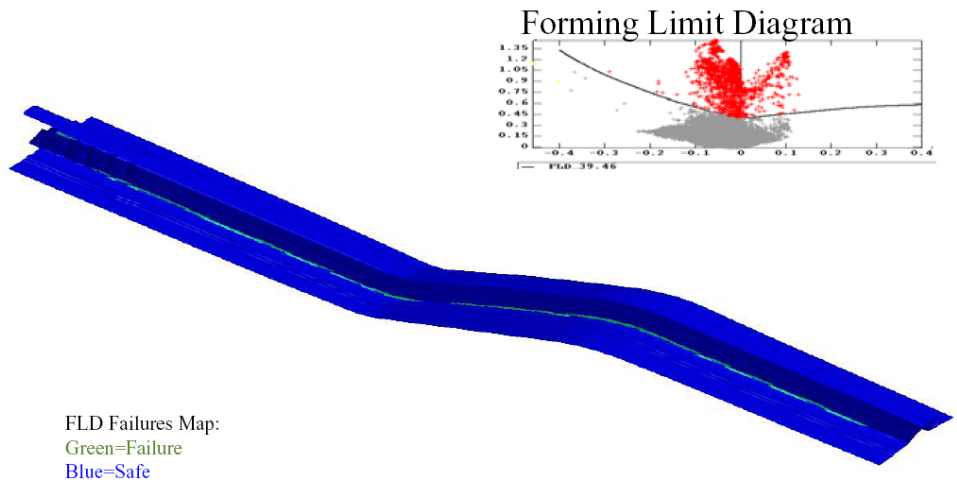
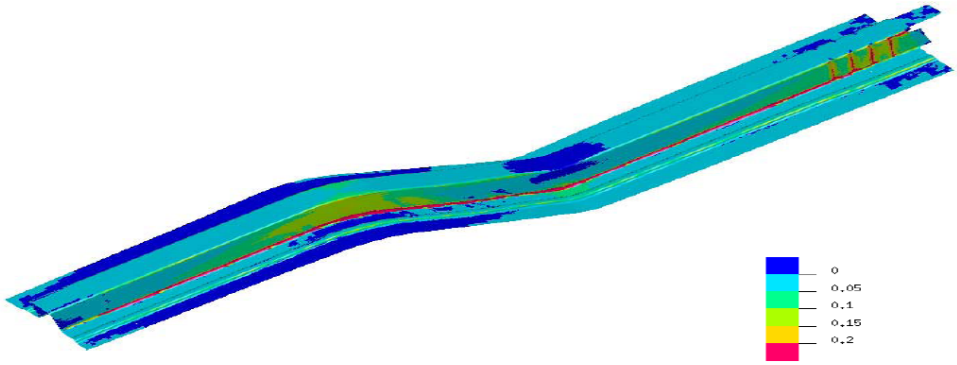
FORMABILITY ANALYSIS



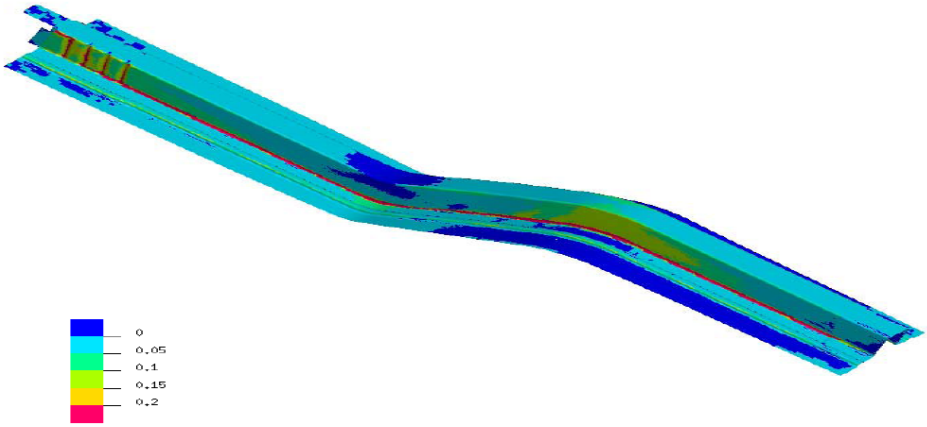
FORMABILITY ANALYSIS

Thinning Distribution Map



FORMABILITY ANALYSIS

Thinning Distribution Map



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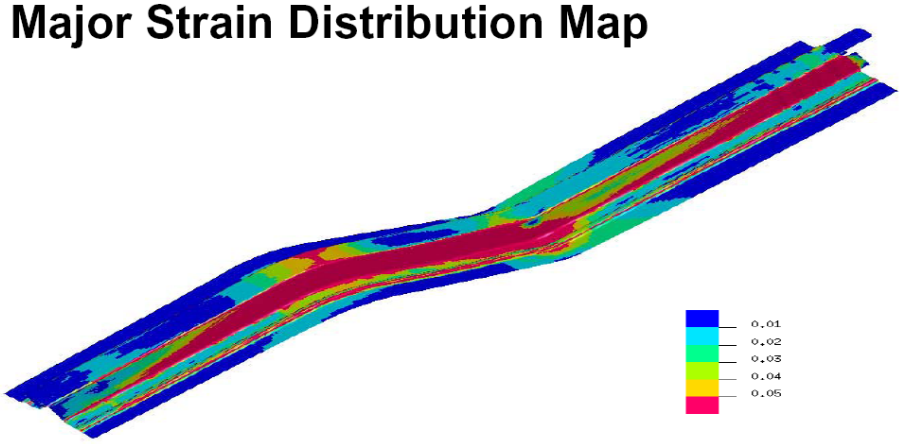
FORMABILITY ANALYSIS

Major Strain Distribution Map



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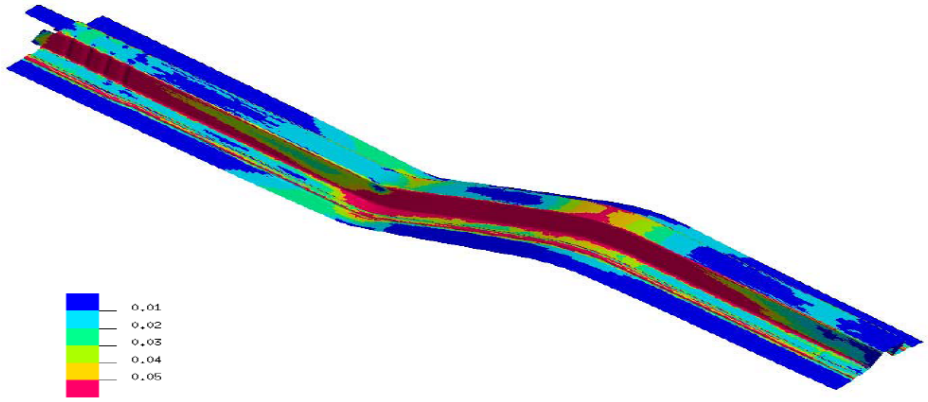
FORMABILITY ANALYSIS

Major Strain Distribution Map



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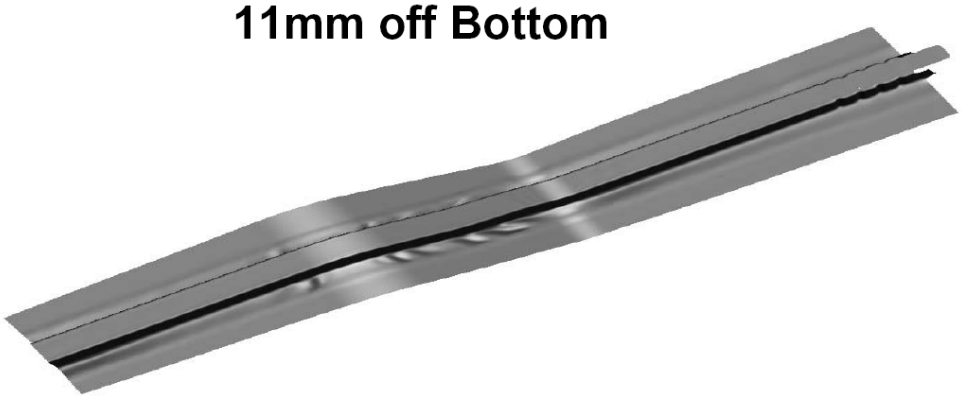
FORMABILITY ANALYSIS

11mm off Bottom



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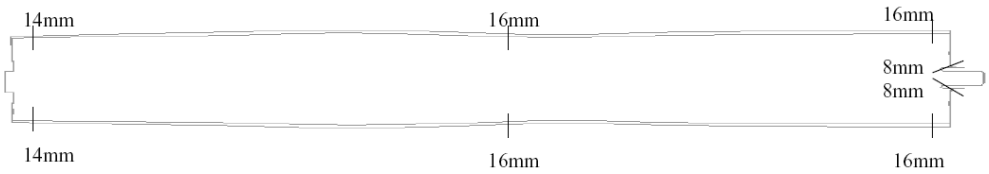
FORMABILITY ANALYSIS

Drawn In Amount Dimensions from 11mm to Closed



DIE PROCESSING

PRESS LINE CONSTRAINTS

Press line assigned to this part.

Press #1: Type	Muller (Hyd) Toggle	Bed size	158 x 94	Press tonnage	2000
Press #2: Type	Verson (Mech)	Bed size	102 x 72	Press tonnage	1000
Press #3: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #4: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #5: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000

Target production rate - 375 / hr

Delay system used in draw die.

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PRESS LINE CONSTRAINTS

Secondary Press line.

Press #1:Type	Verson (Mech) Toggle	Bed size	144 x 84	Press tonnage	600/1000
Press #2: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #3: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #4: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	600
Press #5: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	600

Target production rate - 375 / hr

Delay system used in draw die

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STAMPING PROCESS DESIGN

Process Flowchart:

Blank	Wash & Lube	Forming Operation	Second Operation	Third Operation	Fourth Operation	Fifth Operation
Partially developed rectangular blank	Roll Coat	Toggle Draw with Delay Pad	Trim, Pierce,	Cam restrike both sides & flange	Pierce, cam pierce	Pierce, cam pierce and cam flange

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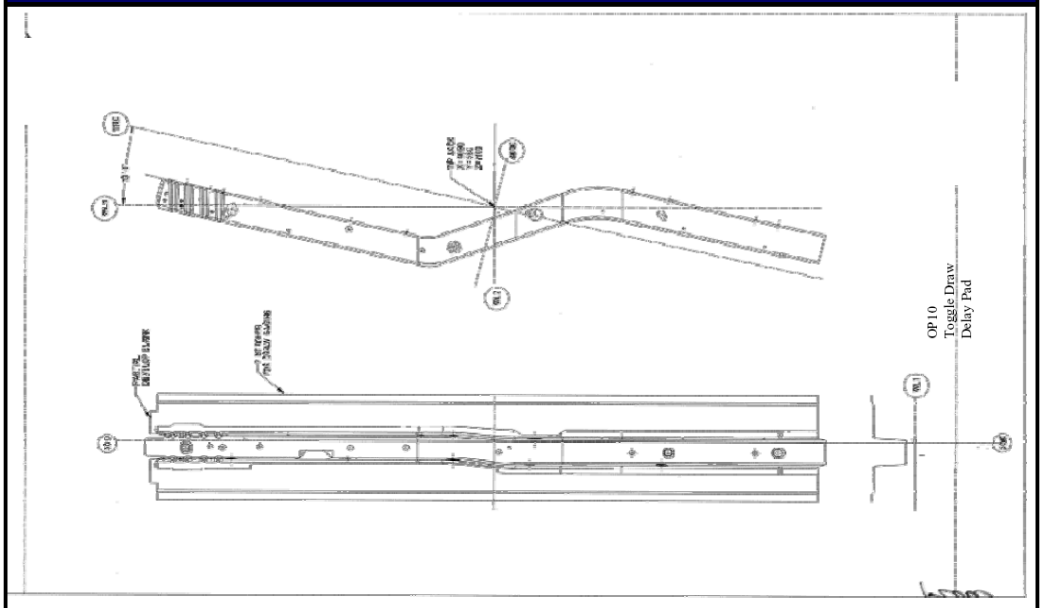
DIE PROCESS



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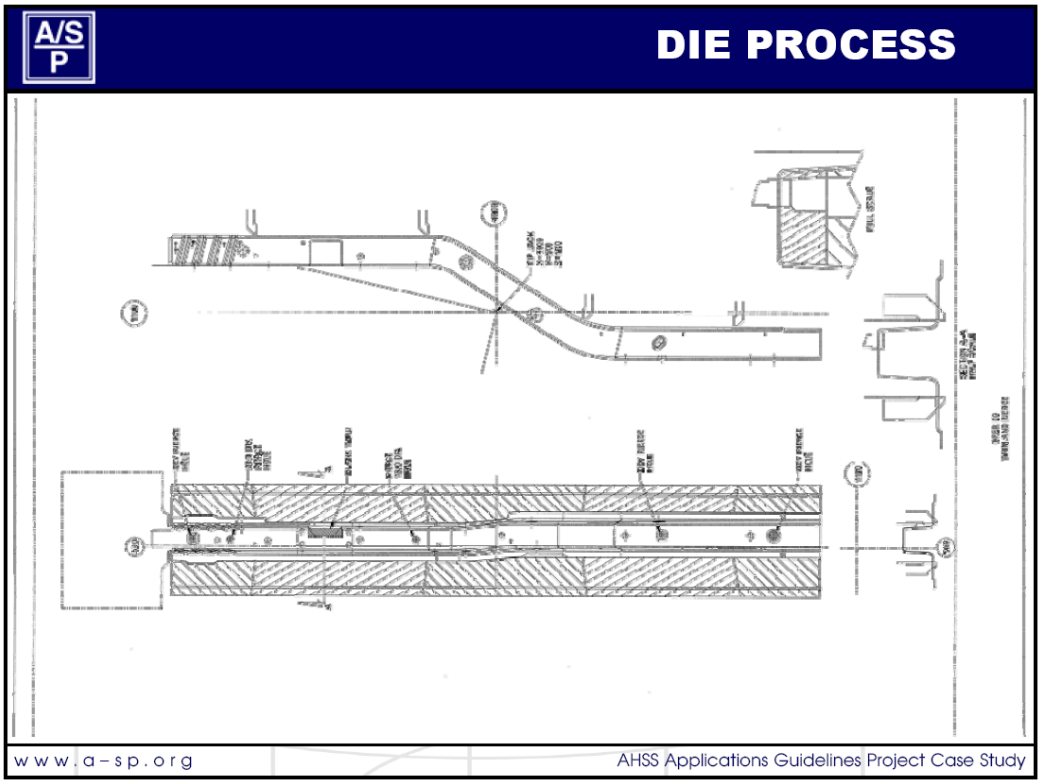
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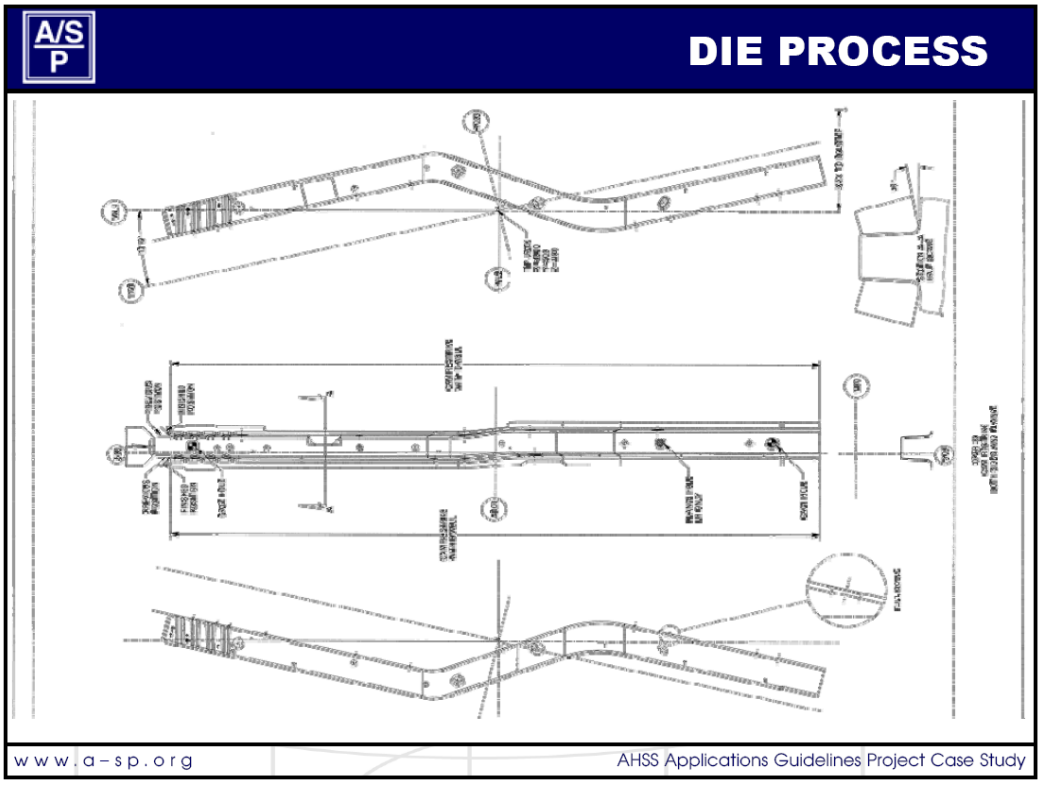
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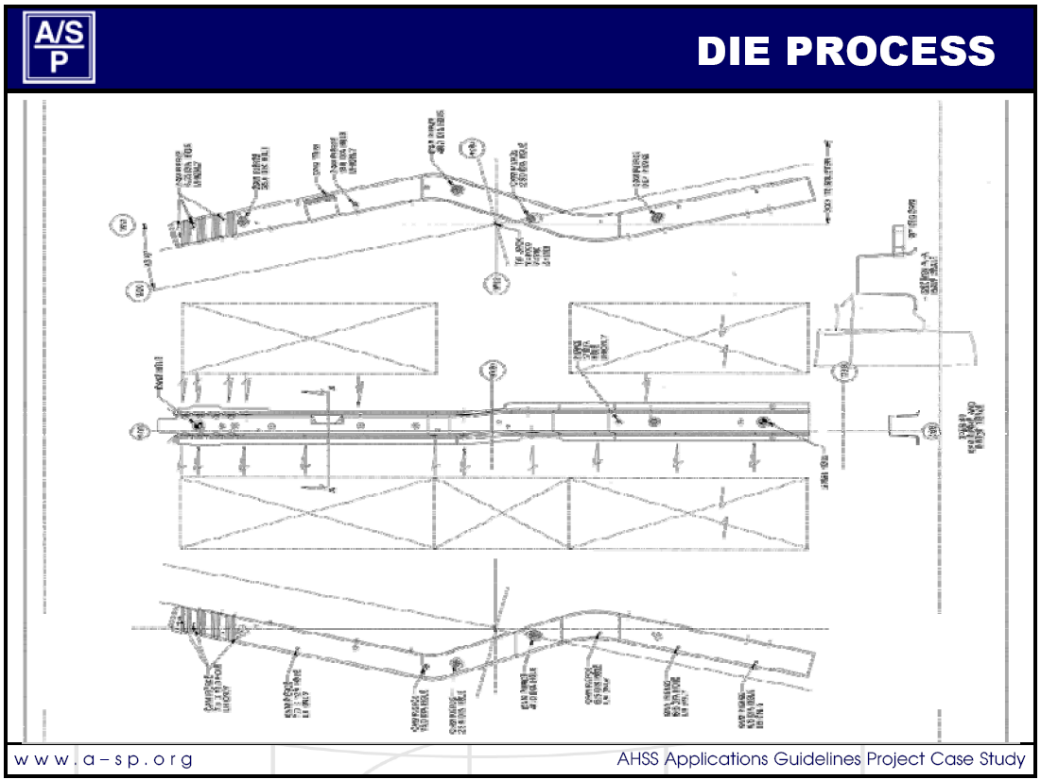
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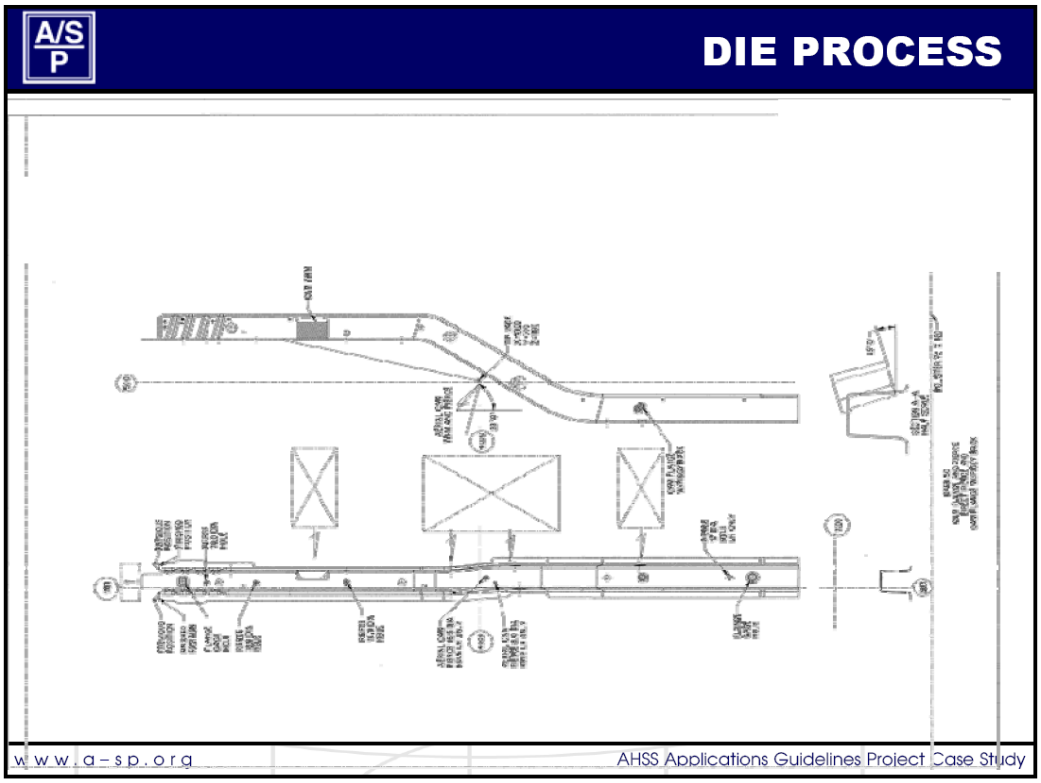
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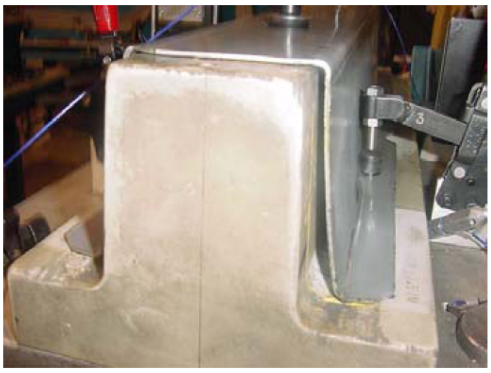
DIE CONSTRUCTION & TRYOUT

SIDE WALL CURL



Before

After

Before and after tuning in the draw die

- Adjust standoffs
- Adjust binder pressure
- Polish draw radii

SPRINGBACK COMPENSATION

Approach to controlling springback

- Morphed draw die for twist and sidewall curl
- Cam restrike to control width

(See following slides)

SPRINGBACK TRIAL

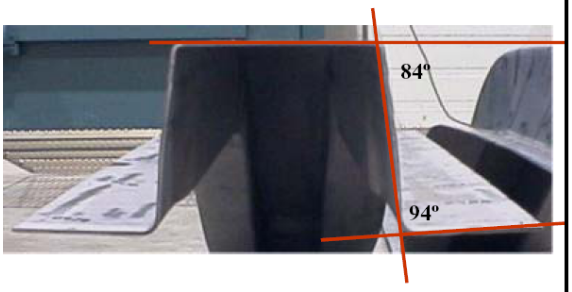
This trial was conducted to demonstrate how DP600 material would perform in a draw die tuned in for 40ksi material.

Blank size and gage was the same for both panels and the press parameters unchanged.

Springback (as shown in the pictures at the right) was much more sever with the DP600 material. Circle grid analysis found the 40ksi material at 10% strain and safe in all areas. The DP600 material was at 9% strain with (2) marginal areas.

DP 600

40 ksi



SPRINGBACK CONTROL MEASURES

Springback controls employed successfully during die tryout:

» Adjusting binder pressure in draw

» Adjusting overbend compensation in cam restrike

Checking fixture was available for die tryout

LESSONS LEARNED

Insights gained during die tryout

- Run dies at production rate during tryout
- Use production draw compound
- Tryout in similar press (Mech, Hyd)
- Trim as close to 90 degrees to surface as possible
- Inserts for flange and radii adjustments

PRODUCTION

PRESS LOAD PREDICTION ACCURACY

Die Stage	Press Loads (Tons)				
	Estimate	CAE Prediction	Actual Measured	Total Available	%
Forming Press	750	N/A	602	2000	30
Binder	350		180		9
Trim, Pierce	350	N/A	250	1000	25
Cam Restrike, Flange	500	N/A	700	1000	70
Pierce, Cam Pierce	300	N/A	250	1000	25
Pierce, Cam Pierce Cam Flange	300	N/A	250	1000	25

POST-LAUNCH EXPERIENCE

INSIGHTS GAINED DURING PRODUCTION

- Tool maintenance intervals 50,000 hits
- Heat buildup issues Drawing Compound
- Tool wear rates Form Dies – polish 50,000 hits, weld critical radii 150,000 hits
- Tool breakage problems: Chipped edges – should PM after each run
- Springback problems: Minor variation run to run
- Dimensional stability and robustness: Minor part variation run to run but stable within the run
- Steel property variability effects: Splits and strains. Cause of run to run variation
- Die tweaks during production to solve problems: Draw die gage and nitro adjustment. Spray application for draw compound where needed.

POST-LAUNCH EXPERIENCE

Rear Rail Split Problem Areas

POST-LAUNCH EXPERIENCE

THINGS DONE DIFFERENTLY NEXT TIME

- No knife edge trim conditions – as close to 90 degrees to surface as possible
- Any unusual shapes or notch trim conditions would be inserts and considered perishable items
- A more robust tool design would be considered in the draw and form dies with inserts for adjustment.
- Coated steels would be considered in high wear areas.
- Pin point spray lube system would be used in the draw die.

Case Study Summary #4

Part Name	Plate-Underbody Side Rail	**Material/Grade :** DP 420/780	**Thickness:** 1.50 mm
Coating :	Uncoated	**URL for Full Case Study:**	www.a-sp.org/publications.htm

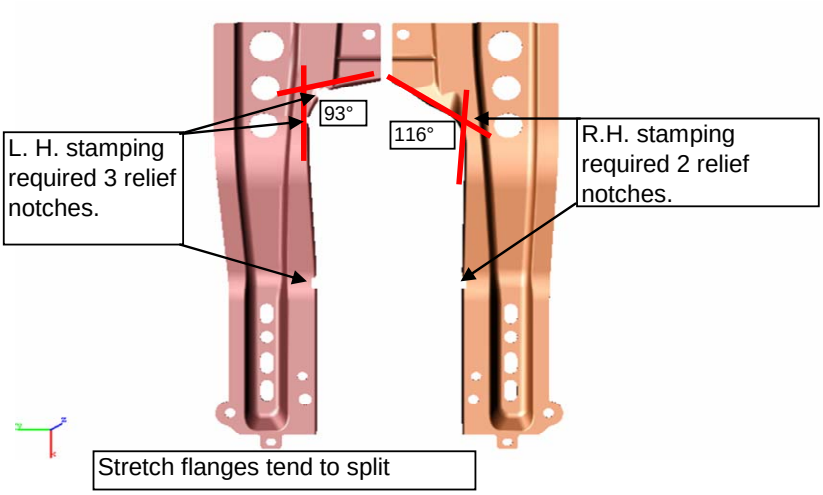
Spring-back/Twist Countermeasures: Draw, Flg. & Restrike Dies cut with compensation for springback & twist.

Manufacturing Process

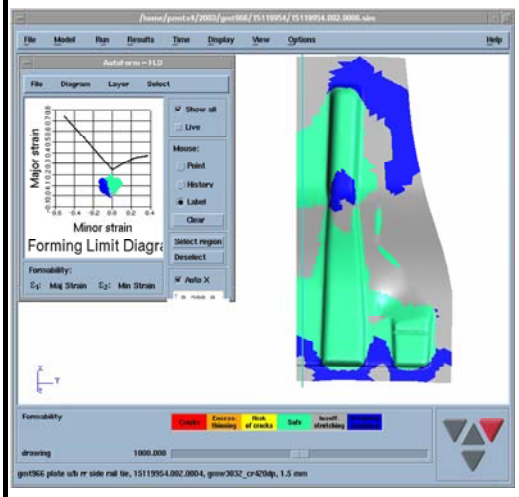
No. of Dies- 5	Dbl. Draw	Trim & Pierce	Form & Trim	Pierce & Trim	Restrike & Separate		

Diagrams / Illustrations

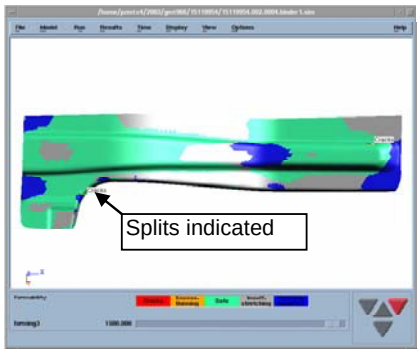
Part Geometry



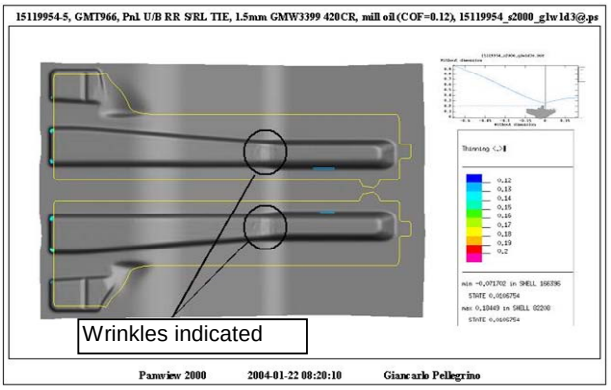
FLD



Die construction considerations



Do not reform work hardened areas.

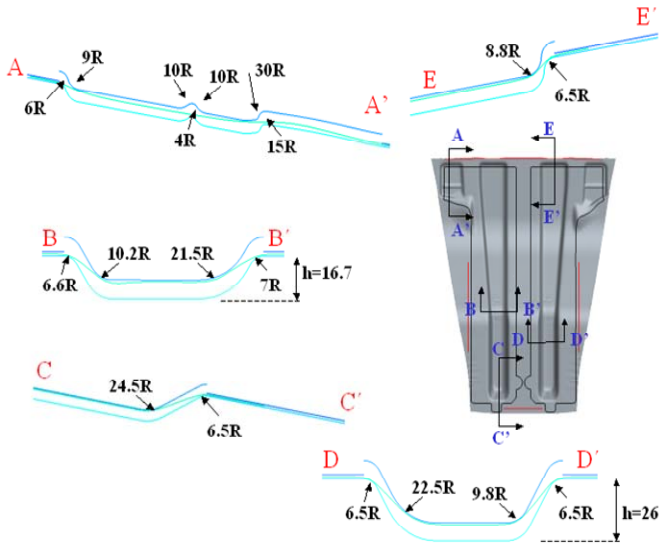


Product Design Notes

Stretch flange conditions will require relief notches.

DP 780 is more sensitive to stretch flange edge splits.

Section Information



CASE STUDY #4:
PLATE - UNDERBODY REAR SIDE RAIL

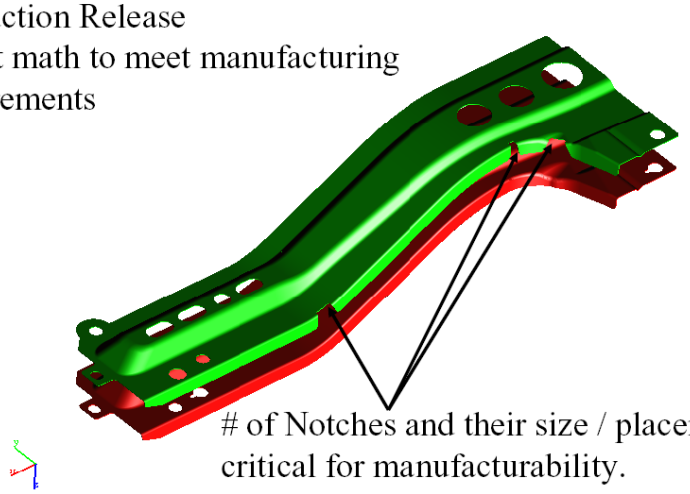
Jeff Powell
Global Stamping Architect
Advanced Vehicle Die & Stamping Engineer
General Motors Corporation
gm.com
jeff.powell@gm.com

PART DESCRIPTION

Part Name: Plate-Underbody Rear Side Rail Tie

Draw Depth: 30mm Toggle Draw

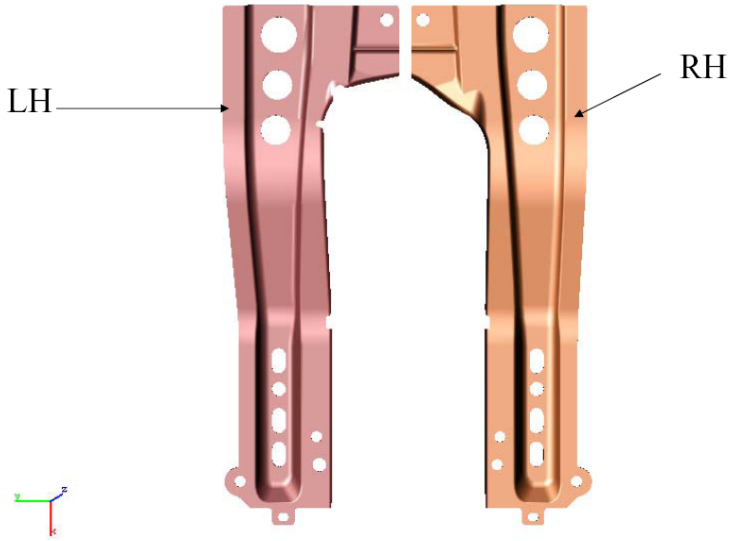
Red = Production Release
Green = Latest math to meet manufacturing requirements



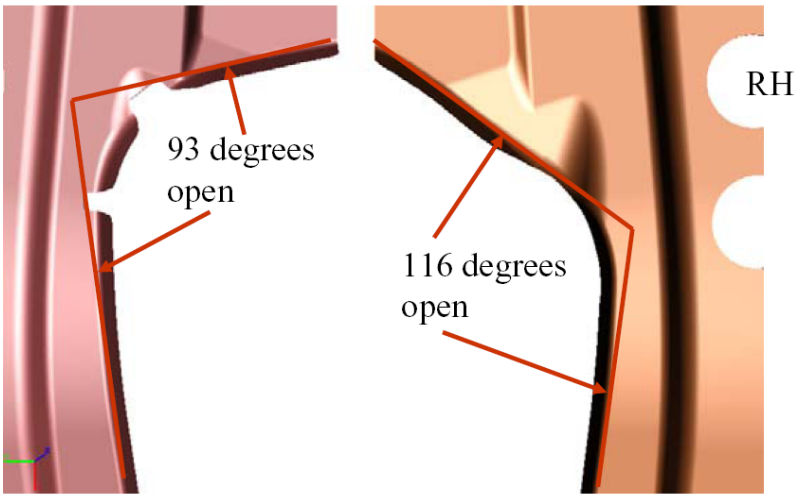
# of Notches and their size / placement is critical for manufacturability.

PART DESCRIPTION

RH to LH Comparison
LH has 3 notches in the flange
RH has 1



PART DESCRIPTION

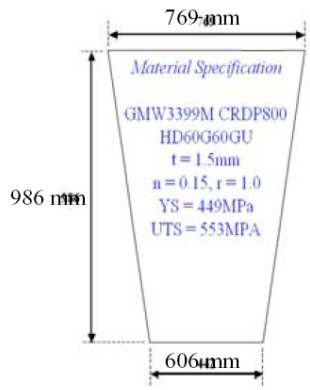


MATERIAL DESCRIPTION

Steel Grade:	DP 780 (420Y/780T) CR
Coating:	HD60G60GU / Bare*
Gauge:	1.50 mm
Blank Width:	986 mm
Blank Pitch:	606 mm
Blank Shape:	Trapezoid
Lubrication:	Mill Oil

Steel vendors different for primary tryout and production. The vendor was not changed due to manufacturability issues

BLANK SIZE AND SHAPE



YS: 449 MPa UTS: 553 MPa

n-value: 0.15 r-value: 1.0

*Material changed from HD to Bare per product request.

PRESS LINE CONSTRAINTS

Press #1: C-Class – Tri-Axis Transfer Press
Toggle Draw

Estimated production rate = 19.5 SPM

Factors that led to this press line assignment:

Toggle action & turnover capability (CL2C)
Formability requires more than 100 tons of binder pressure.

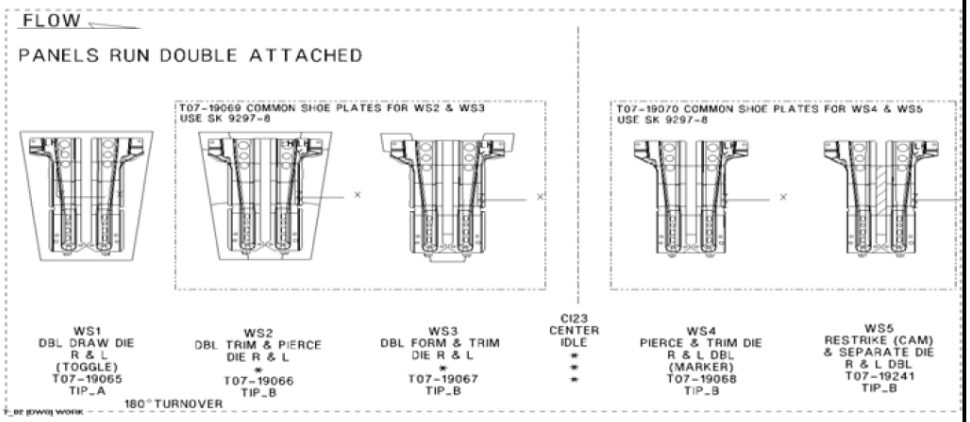
STAMPING PROCESS DESIGN

Process Overview

Forming Process Type: Draw Forming

Process Flow:

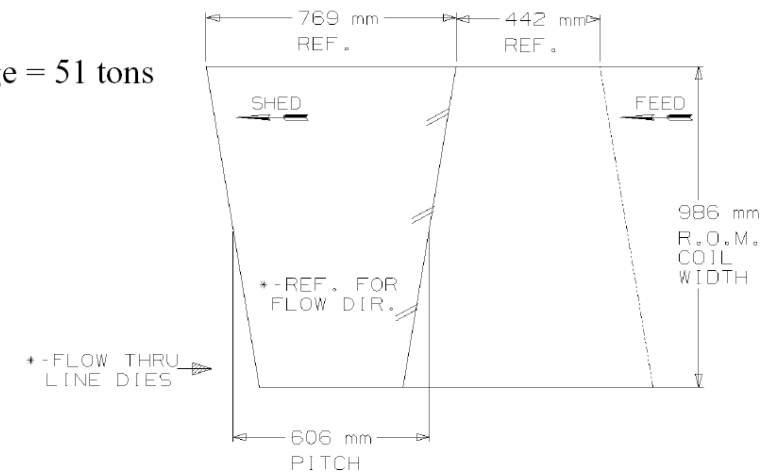
Trapezoid Blank → DBL Toggle Draw → DBL Trim & Pierce → DBL Flange & Trim → Center Idle → DBL Pierce & Trim → DBL Restrike (Cam)& SEP



STAMPING PROCESS DESIGN

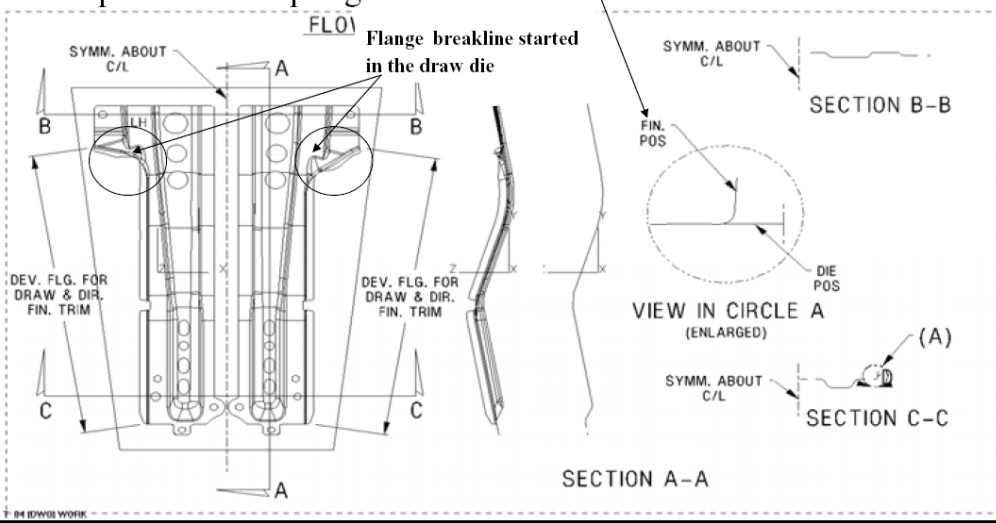
Blanking Operation: Oscillating Die-Standard Equipment

Purchased Blanks
1BLK=2PRTS
Estimated Tonnage = 51 tons

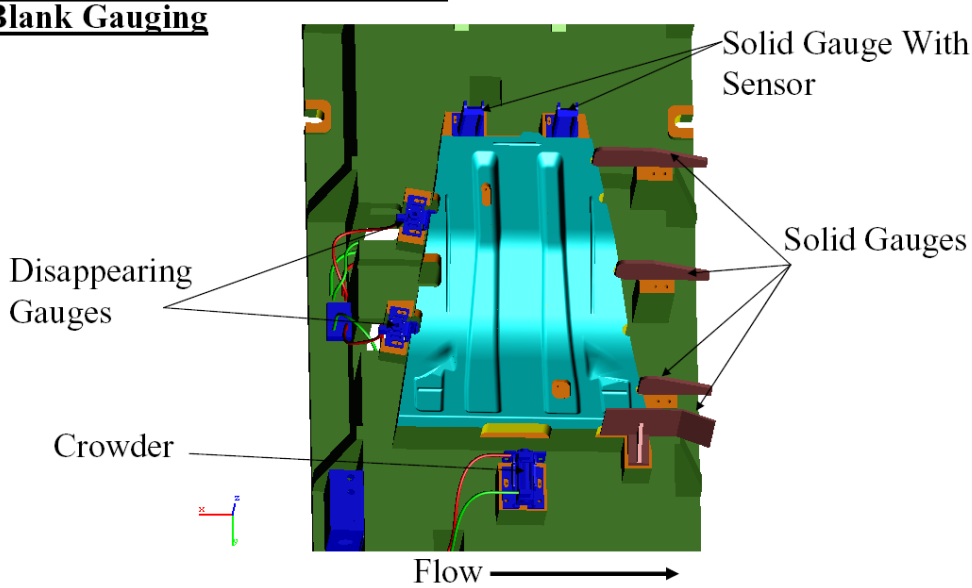


First Die Operation – Draw Die

Draw Complete except for developed flange. Draw development compensated for springback



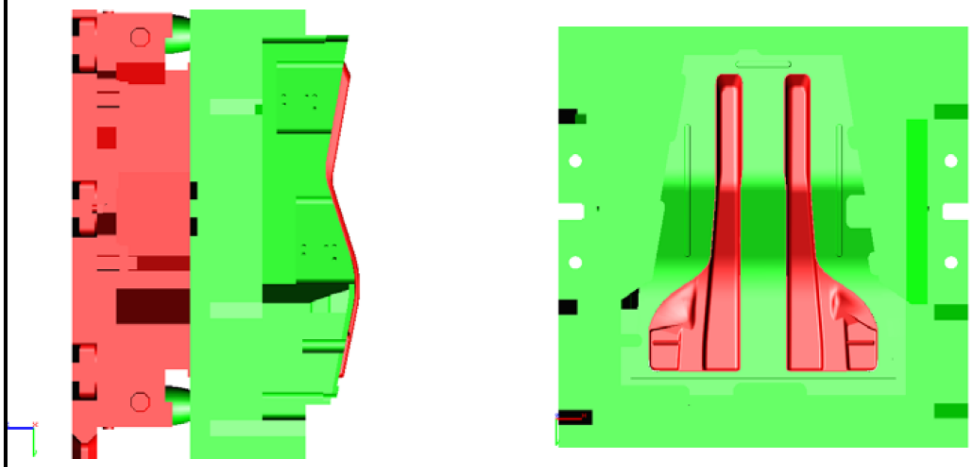
First Die Operation – Draw Die Blank Gauging



STAMPING PROCESS DESIGN

First Die Operation – Draw Die
Upper Binder & Punch

Binder = Green
Punch = Red



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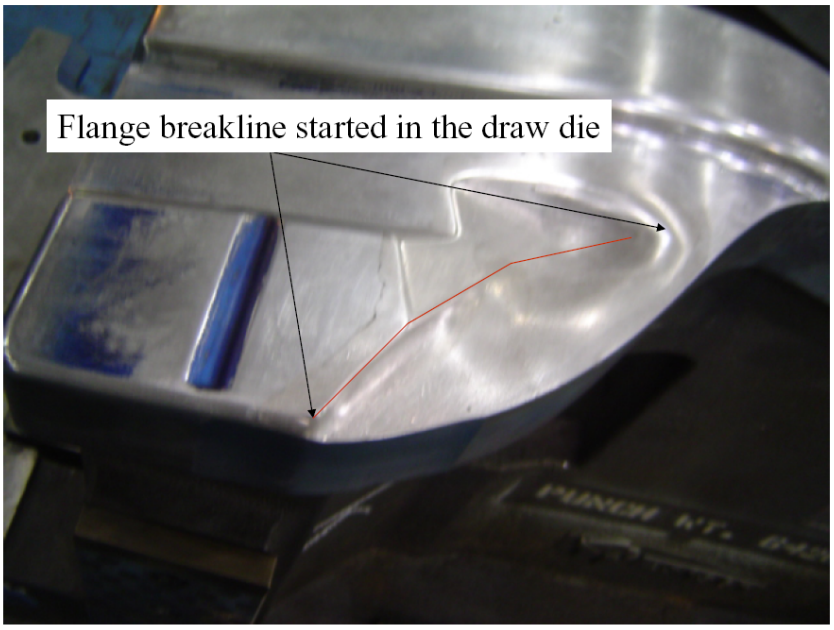
STAMPING PROCESS DESIGN



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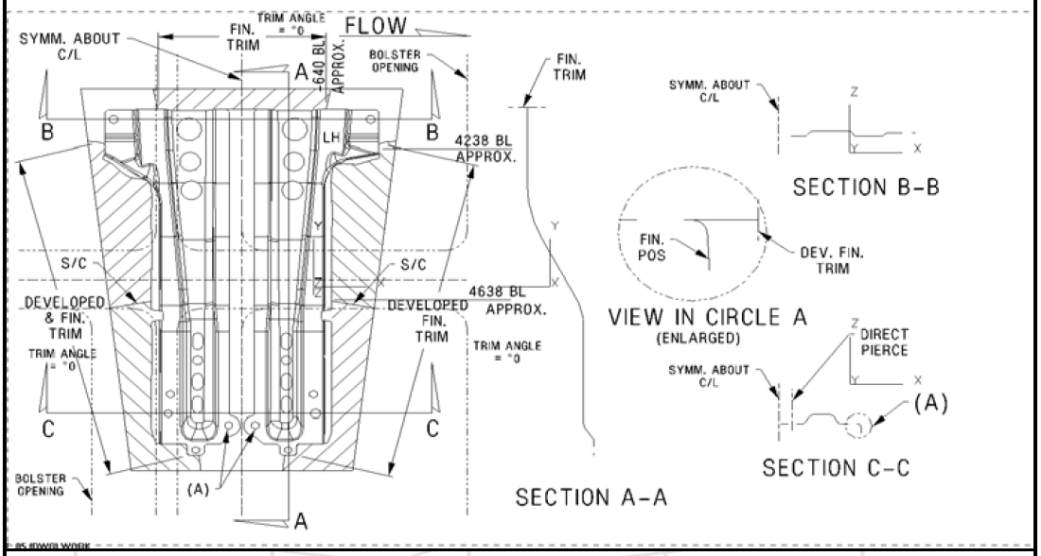
STAMPING PROCESS DESIGN

Second Die Operation – Trim & Pierce Die

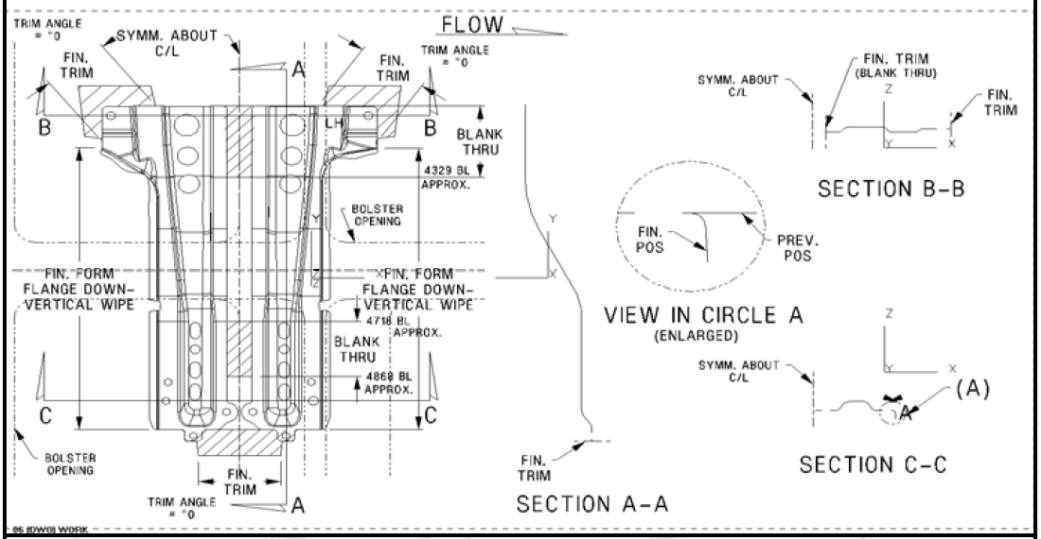
Developed finish trim (direct) in the flange area. Panel rotated 180 degrees for line dies-flange up to flange down.



STAMPING PROCESS DESIGN

Third Die Operation –Flange & Trim Die

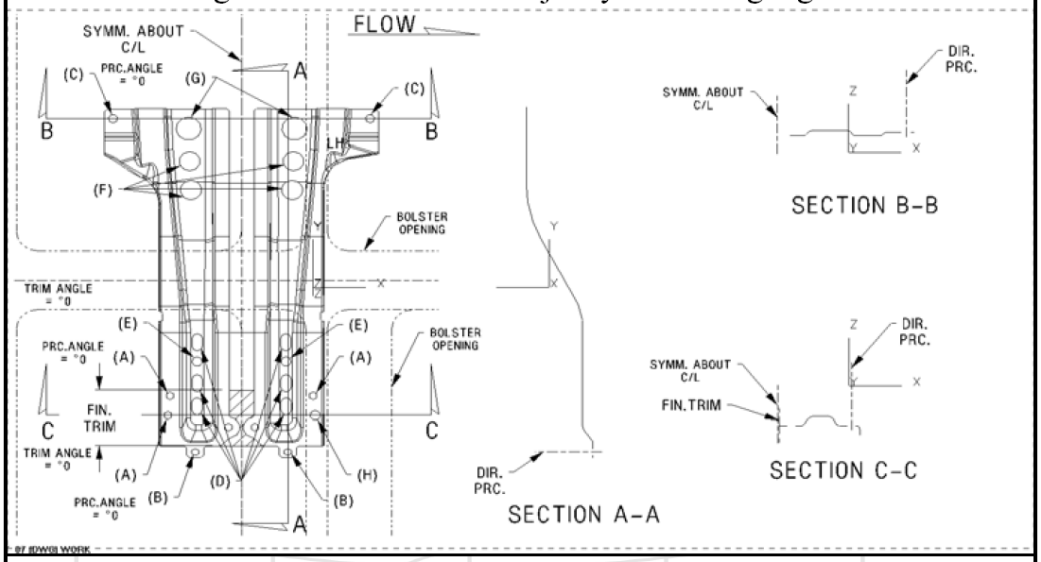
Continue stage trim & flange down-vertical wipe



STAMPING PROCESS DESIGN

Fourth Die Operation – Pierce & Trim Die

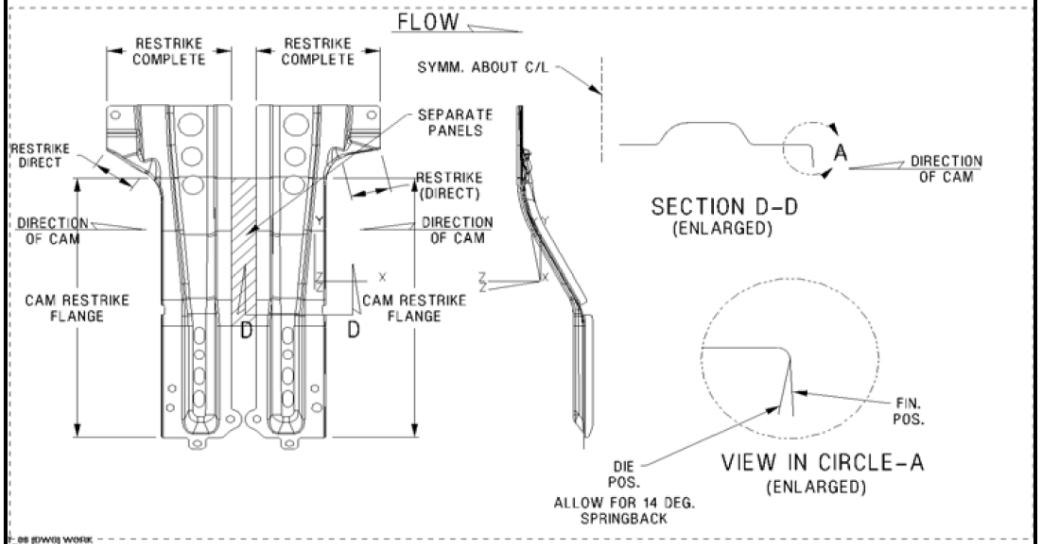
Continue stage trim & Pierce the majority of holes-gauge



STAMPING PROCESS DESIGN

Fifth Die Operation – Restrike (Cam) & Separate Die

Finish stage trim & Restrike the flange (direct & Cam) & end of panel

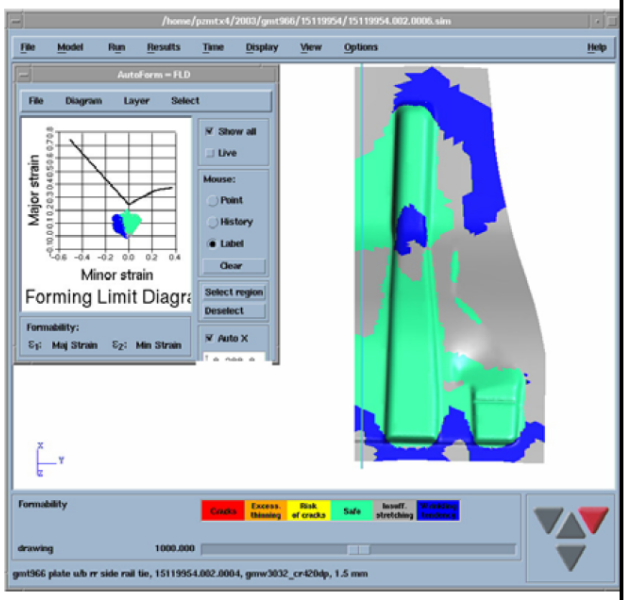


FEA FORMABILITY ANALYSIS

- Autoform & PamStamp Analysis used for Formability Simulation
  - Areas exhibiting high strain or thickening where corrected in product design
    - Critical Forming Radii are listed on following slides
    - Notches added for flange stretch / compression issues
- Worse Case Mechanical properties were used in analysis
- 0.15 Coefficient of friction used for analysis

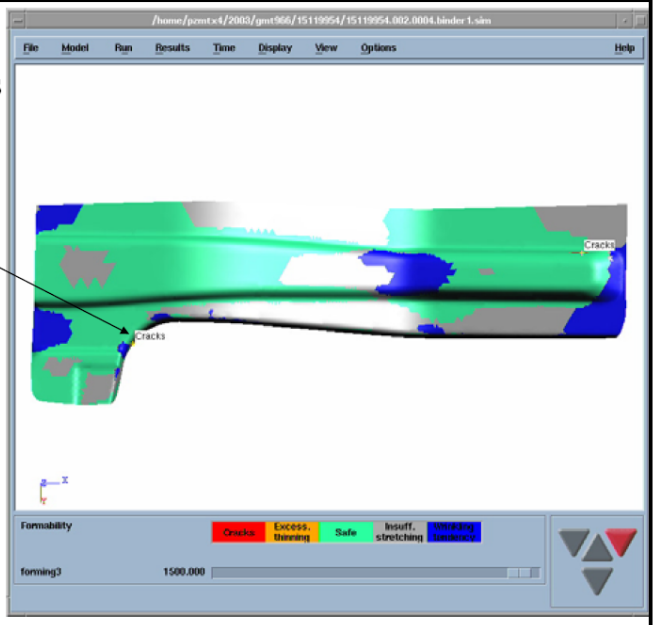
FEA FORMABILITY ANALYSIS

Draw Analysis in autoform passing at data release.



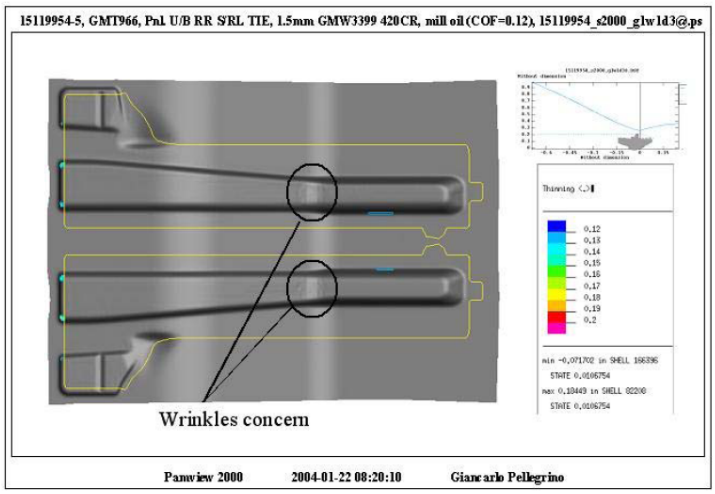
FEA FORMABILITY ANALYSIS

Autoform Flange Analysis
Splits anticipated in the corner



FEA FORMABILITY ANALYSIS

Rectangle Blank

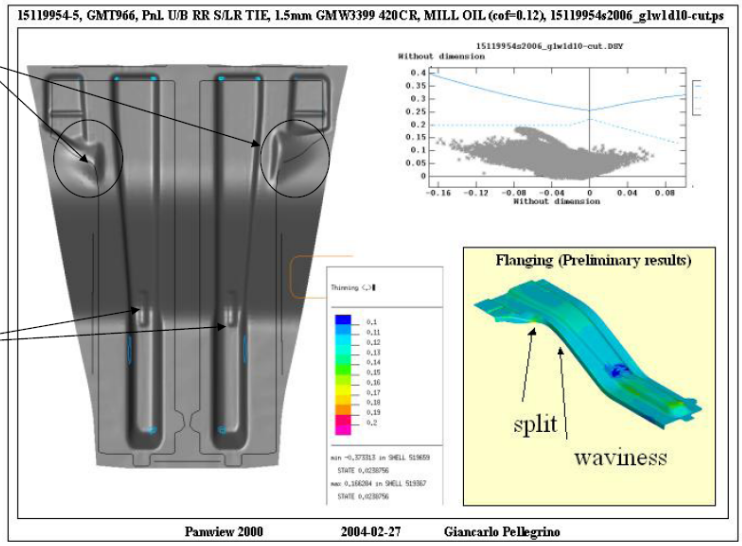


FEA FORMABILITY ANALYSIS

Trapezoid Blank

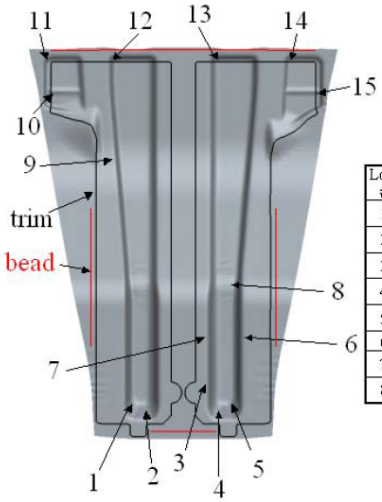
Area is work hardened, prior to the flanging operation

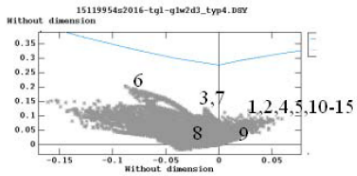
Take-ups not utilized



FEA FORMABILITY ANALYSIS

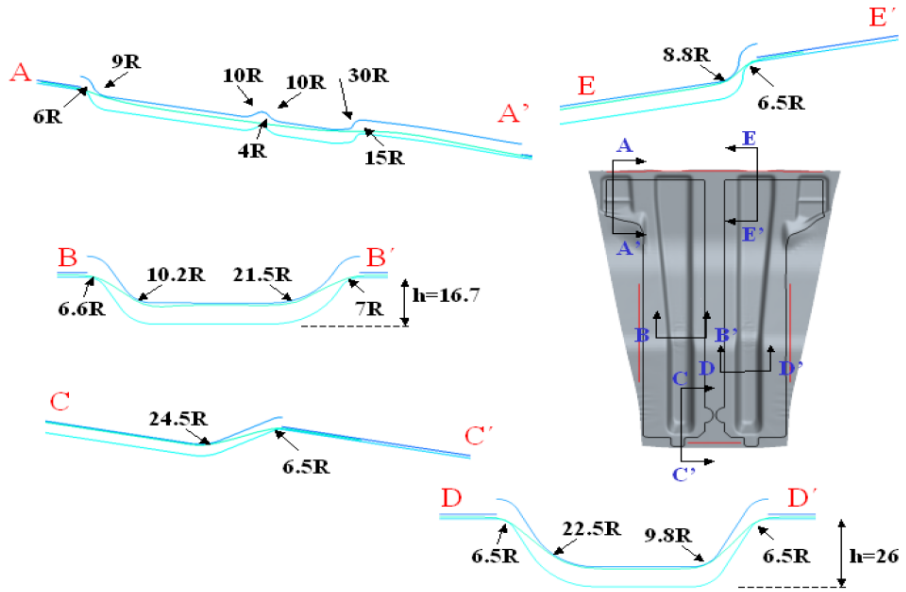
Passing draw analysis





Loc. #	Thinn.	Major Strain	Minor Strain	Loc. #	Thinn.	Major Strain	Minor Strain
1	10.3	8.1	2.8	9	3.7	3.5	0.4
2	12.9	9.2	4.6	10	11.5	8.4	3.7
3	9.5	11	-1.2	11	9.8	9.4	0.9
4	12.9	9.3	4.6	12	13.5	11.7	2.8
5	10.4	8.5	2.5	13	13.8	8.9	5.9
6	10.6	17.8	-6.5	14	9.4	6.1	3.7
7	7.5	9.2	-1.3	15	10.6	8.3	2.9
8	-2.4	0.5	-2.9				

CRITICAL FORMING RADII

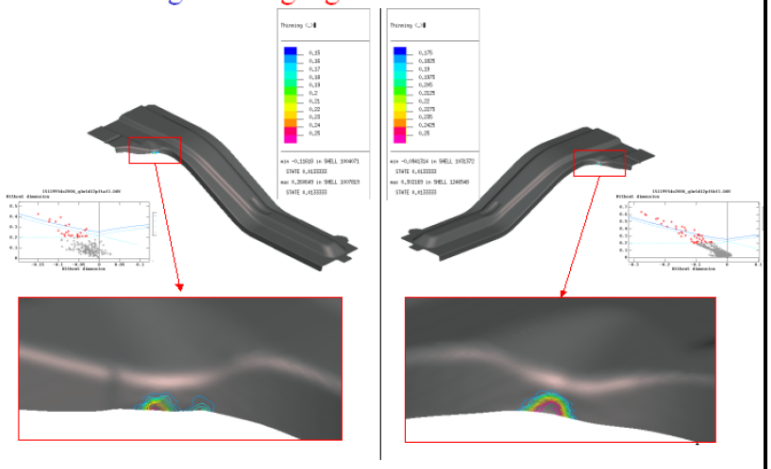


FEA FORMABILITY ANALYSIS

Flanging Analysis

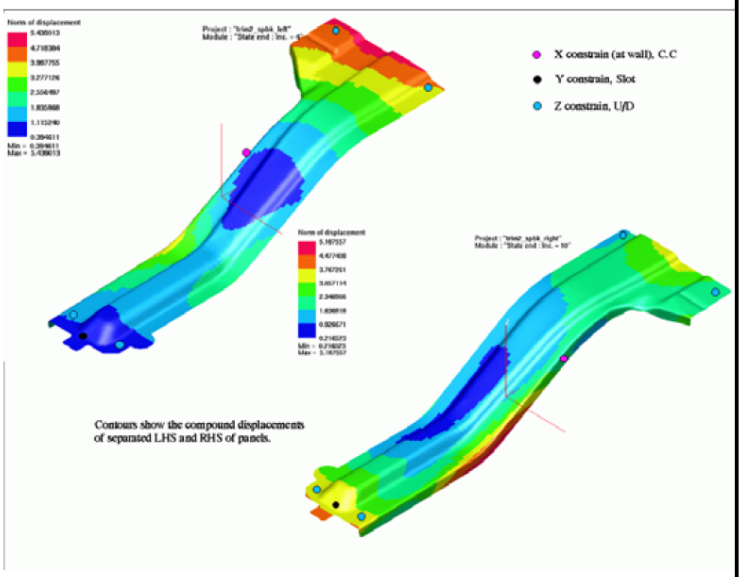
GMT966 – *15119954-5 – Plate U/B RR Side Rail*

Thinning – Flanging



FEA FORMABILITY ANALYSIS

Springback Analysis

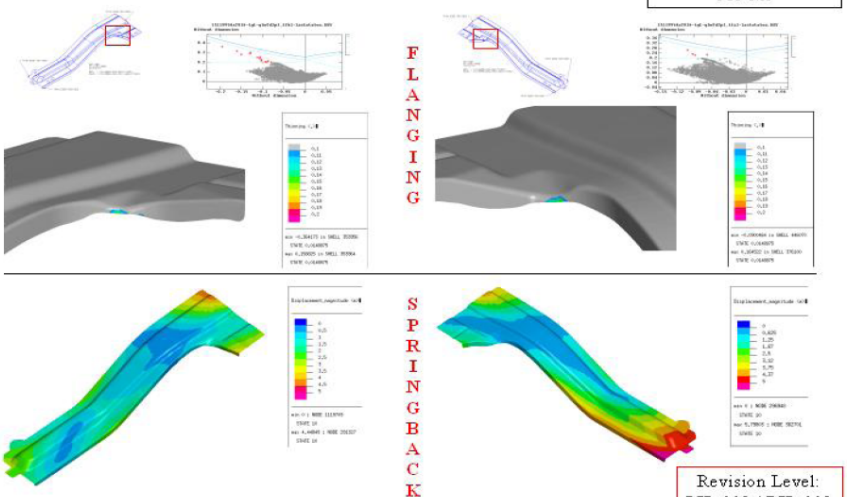


FEA FORMABILITY ANALYSIS

Passing springback & flanging analysis

GMT966 – 15119954-5 – Plate U/B RR Side Rail

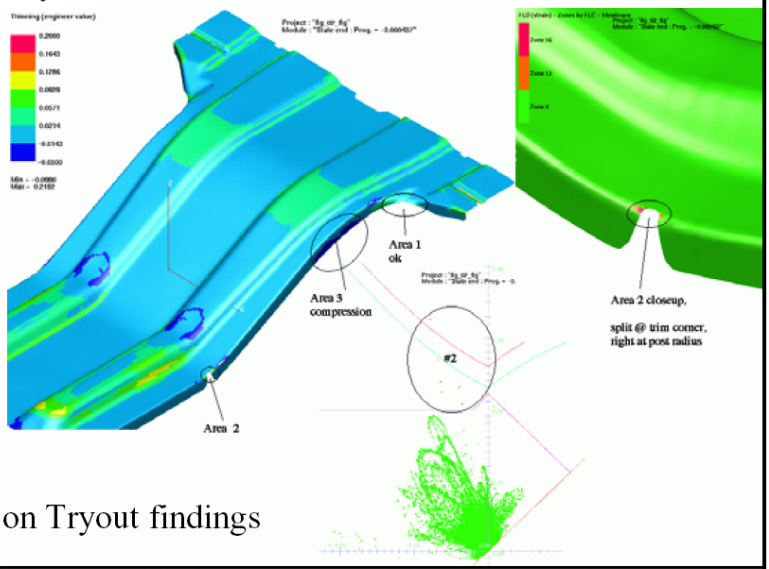
GMW3399-ST-S CR420DP
HD60G60GU 1.5 mm
COF 0.15



Revision Level:
LH: 002 / RH: 002

FEA FORMABILITY ANALYSIS

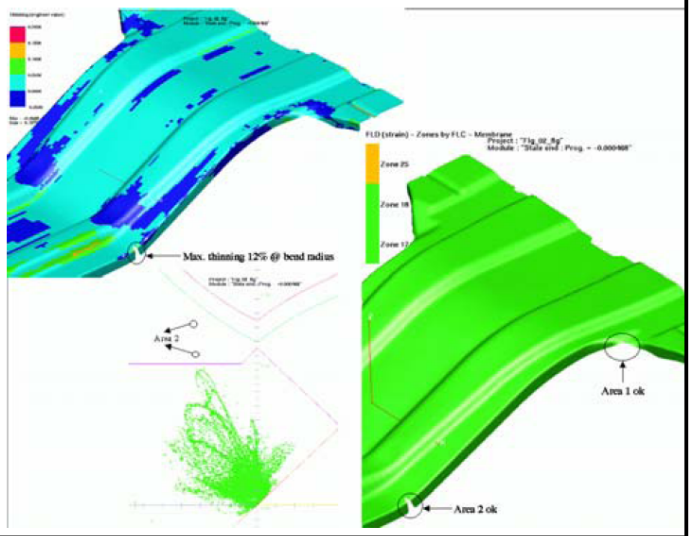
Tryout experienced splitting in the flanging operation. Notches added and optimized based on tryout trial & error-handtrim.



Re-run based on Tryout findings

FEA FORMABILITY ANALYSIS

Final Re-run to match Tryout



NEGOTIATED GEOMETRY CONCESSIONS

Original data

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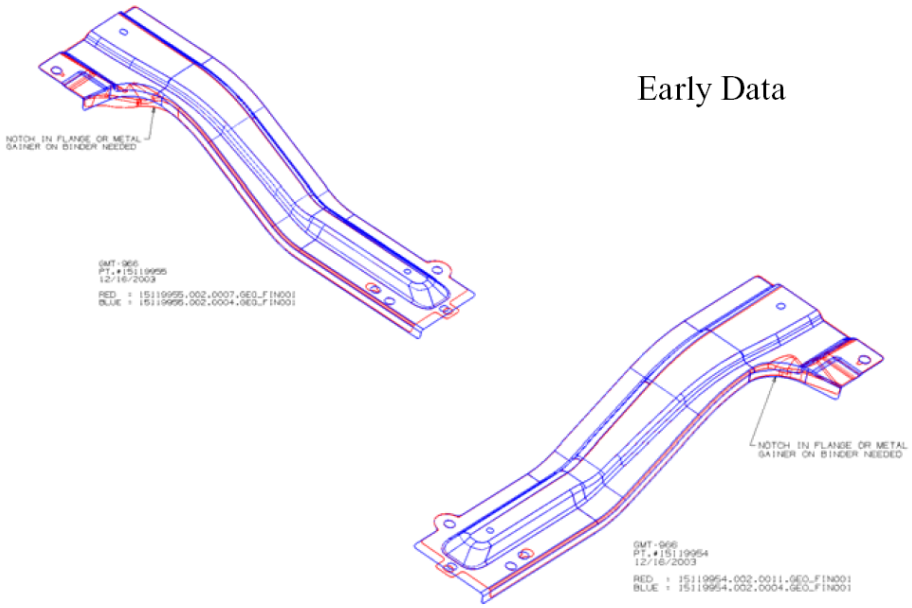
NEGOTIATED GEOMETRY CONCESSIONS

Early Data



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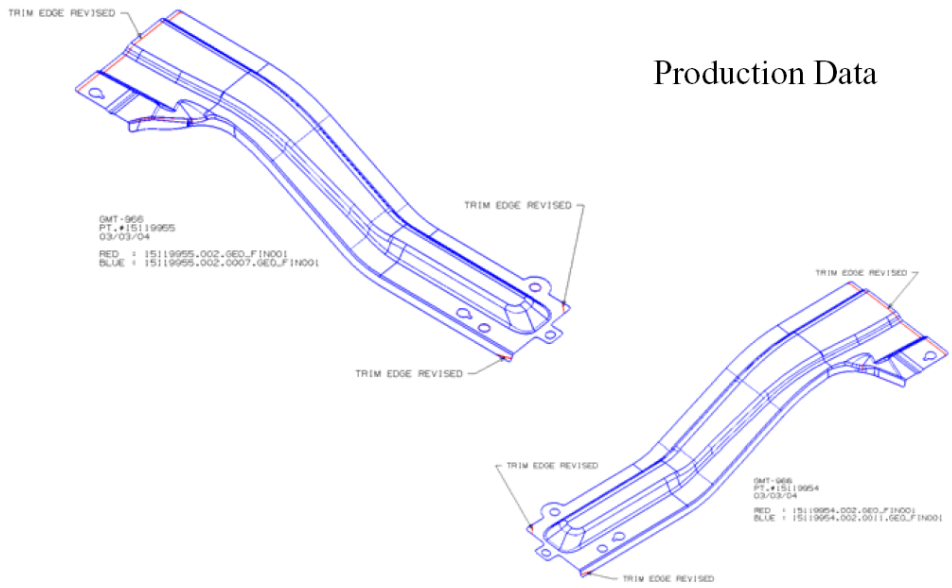
NEGOTIATED GEOMETRY CONCESSIONS



Production Data

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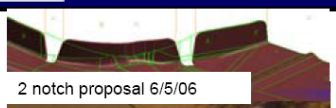
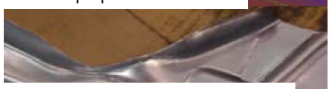
NEGOTIATED GEOMETRY CONCESSIONS



2 notch proposal 6/5/06



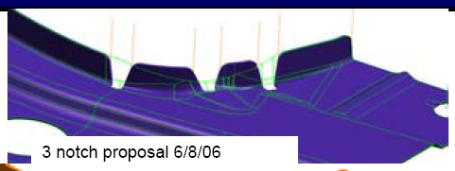
Proposed by DEI 5/16, approved by crash group 5/22/06, still splitting

Revision bv DEI 5/1/06
Not approved by crash group

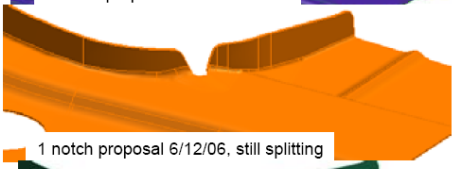
REV .006 7/19/05 (Released Design)

REV .004 3/4/05 (IVER Release version)

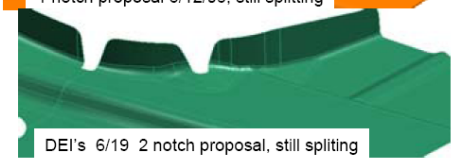
TIME



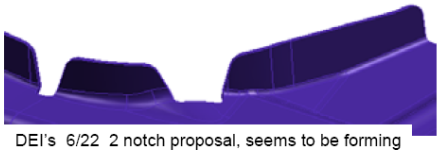
3 notch proposal 6/8/06



1 notch proposal 6/12/06, still splitting



DEI's 6/19 2 notch proposal, still spliting



DEI's 6/22 2 notch proposal, seems to be forming

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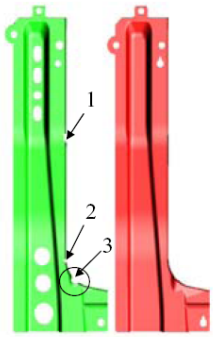
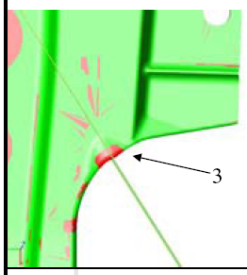
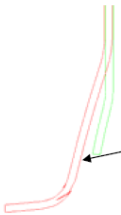
NEGOTIATED GEOMETRY CONCESSIONS

Part Name: Plate-U/B RR S/RL Tie

3 notches added to the flange to alleviate splitting conditions in the flange die. Form also changed in circled area.







~5mm local depth change & trim change (notch addition)

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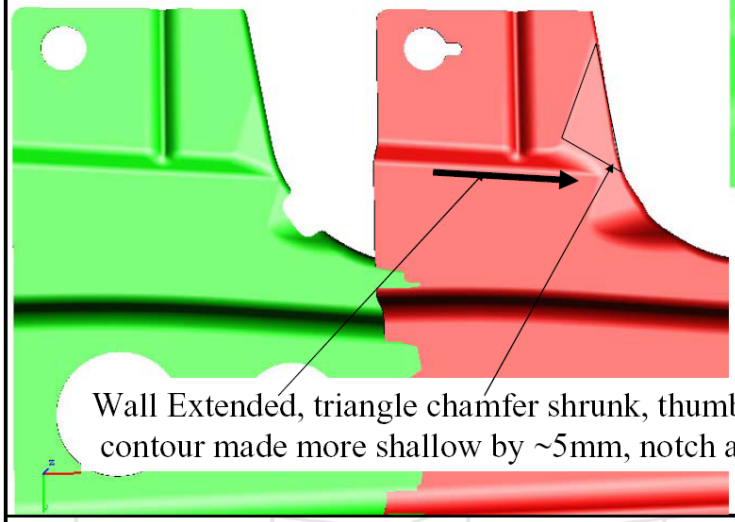
NEGOTIATED GEOMETRY CONCESSIONS

Part Name: Plate-U/B RR S/RL Tie



Wall Extended, triangle chamfer shrunk, thumbnail depression contour made more shallow by ~5mm, notch addition.

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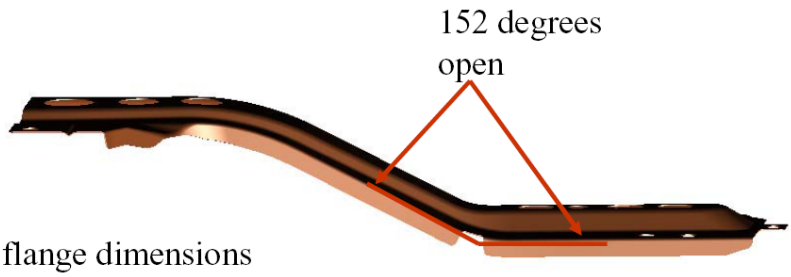
NEGOTIATED GEOMETRY CONCESSIONS

Common Notch



Typical flange dimensions
Angle = 93 degrees to car position
Length = 20mm
Radius = 7.3mm

SPRINGBACK COMPENSATION METHODOLOGY

Describe approach to controlling springback

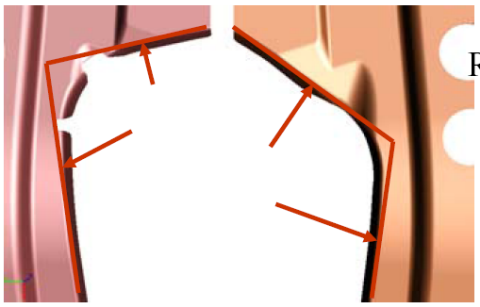
Draw, Flange & Restrike dies were cut with compensation for springback & twist

SPRINGBACK COMPENSATION METHODOLOGY

Retrike die added in the original processing to the line to correct springback

RH vs LH geometry differences proved to have different springback results U/D on the end of the panel & F/A on the flange

LH



RH

SPRINGBACK CONTROL HISTORY / ACCURACY

Not much history with this type of material

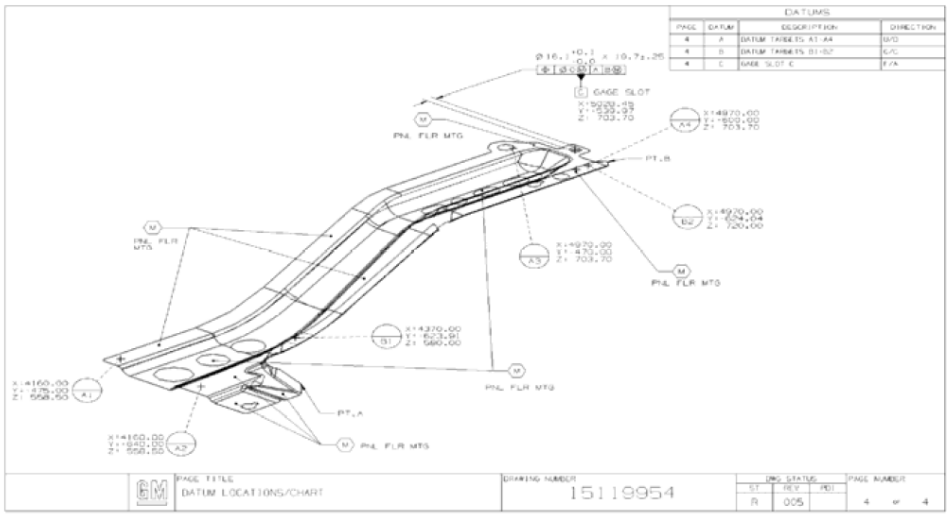
Analysis model not accurate for predicting springback amounts with this type of material.

Vertical flange restrike steels removed on the RH panel as they were taking the flange away from nominal

A second recut is typically required to bring the flanges to nominal

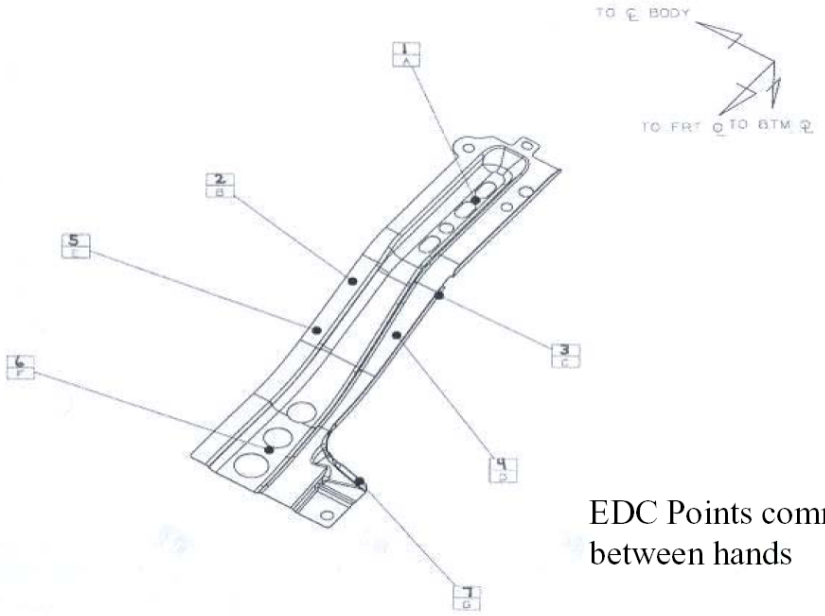
FIXTURING AND CLAMPING

Mating Surfaces & Datum strategy



C/C datum's are on the flange surface!

FIXTURING AND CLAMPING



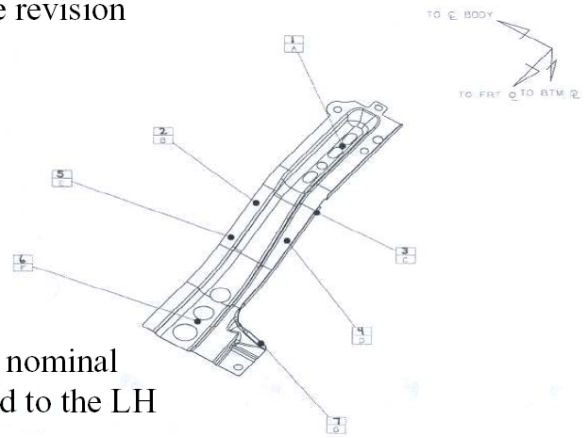
EDC Points common between hands

FIXTURING AND CLAMPING

Original Tolerances are +/- .50 with the target being 0

1 & 6 need retarget with no tolerance revision
2,4 &5 need retarget & tolerance revision
3 needs retarget & tolerance revision
7 needs retarget & tolerance revision

1,2, 4-6	U/D
3	I/O
7	F/A



In general the RH is closer to nominal
& more stable when compared to the LH

POST-LAUNCH EXPERIENCE

Describe any insights gained during production

- Launch is still ramping up
- Not applicable at this time, more information to follow

LESSONS LEARNED

Described insights gained

- DO NOT REFORM WORKHARDENED AREAS
- Design with generous open angles
- Plan for notches right from the start
  - Have the dialog with product early

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Case Study Summary #5

Part Name	A Pillar Front Upper	**Material/Grade :**	DP 350/600	**Thickness:**	1.70 mm
Coating :	HD Galvanneal 40A40A	**URL for Full Case Study:**	www.a-sp.org/publications.htm		

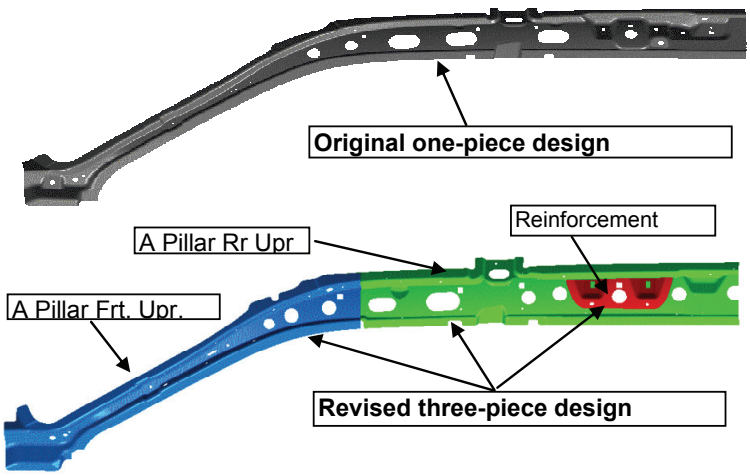
Spring-back/Twist Countermeasures: Cut draw die with compensation for twist and springback. Check to die trimmed panel

Manufacturing Process

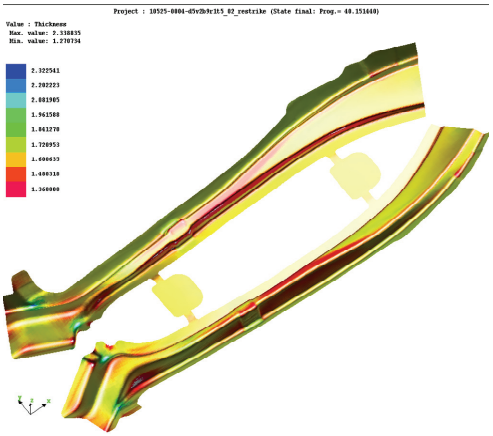
No. of Dies- 5	Dbl. Draw	Trim & Prc,Cam Prc.	Cam Trim & Prc.	Re-Strike	Cam Prc& Separate		

Diagrams / Illustrations

Part Geometry

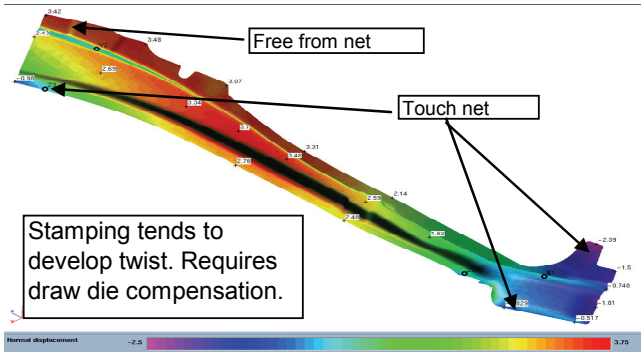


Formability Study

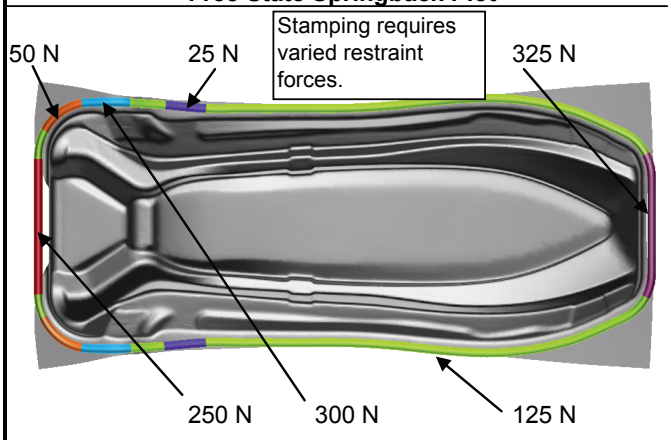


Re-Strike Final Thickness Plot

Die Construction Considerations



Free State Springback Plot



Draw Bead Layout

Product Design Notes

Complex stampings may need to be divided for DP 600.
Modify abrupt surface transitions to avoid splits and metal thinning.
Maintain length of line and depth of draw as much as possible.

Die Construction and Tryout Information

Draw die compensation should be finalized to a die trimmed panel.
Draw / form as much shape as possible in the first die operation.
Provide a robust die construction.
Bottom all form die pads.
Trim as close to 90° to the surface as possible.
Avoid acute angle trimming to reduce trim steel chipping.
Upgrade all tool steels subject to abrasive wear.

CASE STUDY #5:
REINF. – A-PILLAR FRONT UPPER –R&L

Kerry Fitzgerald
AZ Automotive Corp.
AZautomotive.com
kfitzgerald@azautomotive.com

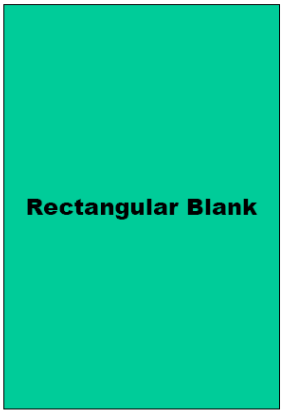
PART DESCRIPTION

Part Name: Reinf-A-Plr Frt Upr RH & LH

- Mating surfaces and critical features:
  - -Flanges all around.
  - -Free state shape
- Critical radii: – Lower End
- Depth of draw: – 108mm

MATERIAL DESCRIPTION

Steel Grade:	DP600 (350Y/600T)
Coating:	HD Galvanneal
Gauge:	1.70 mm
Blank Width:	1270 mm
Blank Pitch:	533 mm
Blank Shape:	Rectangle



Same steel vendor was used for die tryout and production steel supply.

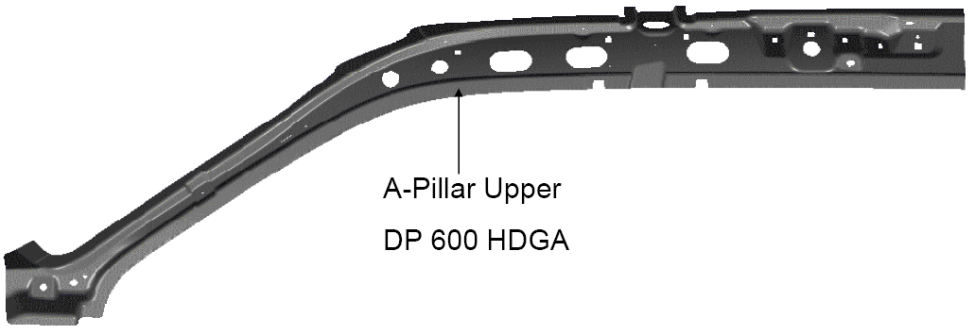
MATERIAL PROPERTIES

Material Properties (metric):

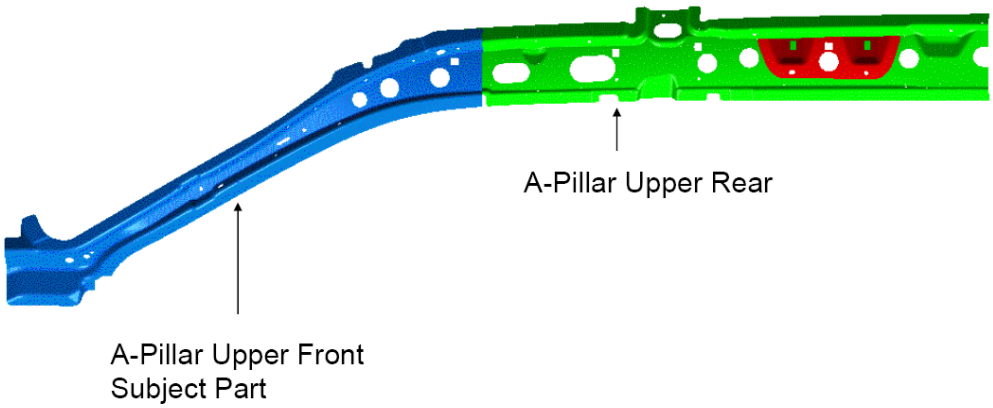
Mat'l:	DP600
Mat'l Thickness:	1.7 mm
Yield:	390 MPa
Tensile:	590 MPa
n-value: (strain range 5 – 15%)	169
r-value:	0.89
K-value:	990 MPa

PART HISTORY

ORIGINAL ONE PIECE DESIGN



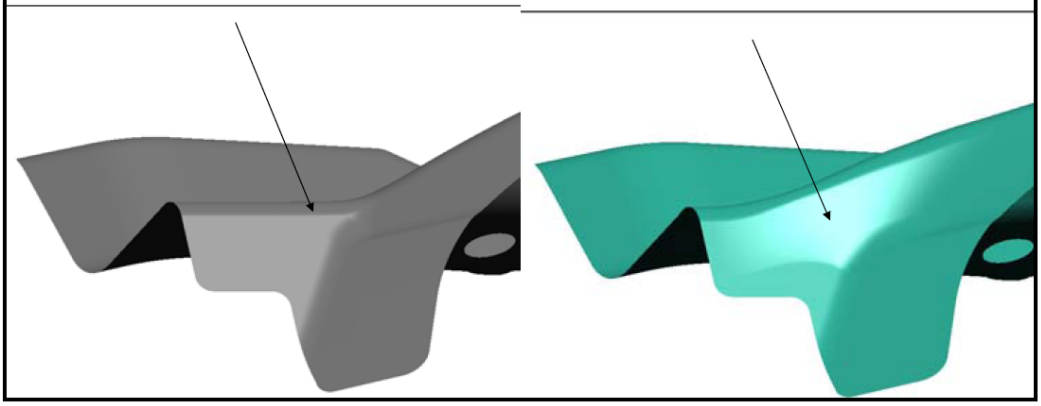
CURRENT DESIGN



NEGOTIATED GEOMETRY CONCESSIONS

Geometry concessions were needed to solve forming and wrinkling issues

From this----------to this



DIE PROCESSING

PRESS LINE CONSTRAINTS

Press line assigned to this part.

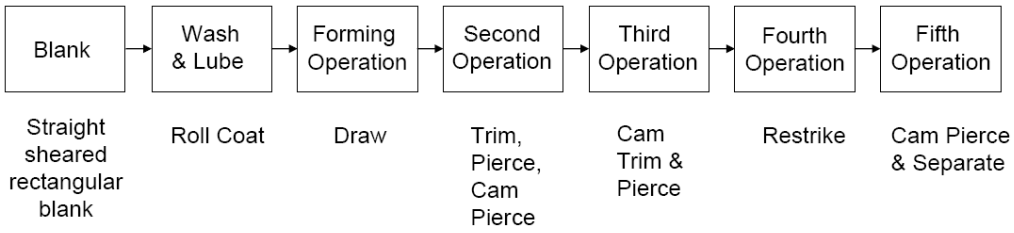
Press #1: Type	Muller (Hyd)	Bed size	158 x 94	Press tonnage	2000
Press #2: Type	Verson (Mech)	Bed size	102 x 72	Press tonnage	1000
Press #3: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #4: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #5: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000

Target production rate - 375 / hr

Die-applied cushion pressure.

STAMPING PROCESS DESIGN

Process Flowchart:
Double Attached



FEA FORMABILITY ANALYSIS

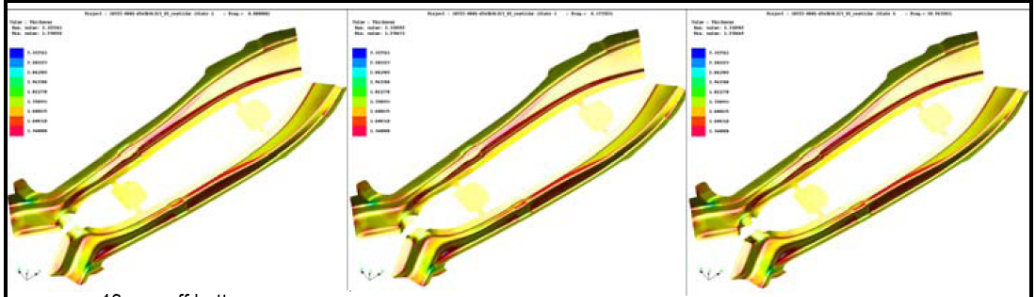
FEA FORMABILITY ANALYSIS

FEA formability study results were much different than what was experienced in die tryout.

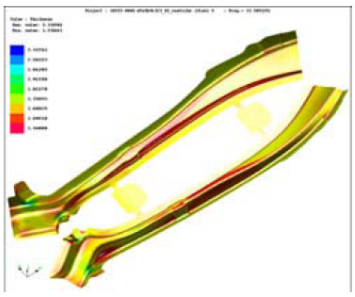
Synopsis of Simulation Results:

- This part doesn't rip or wrinkle; however does thin over 20% .
- The upr Draw binder was simulated with 100 tons of force.
- The lwr Restrike pad was simulated with 80 tons of force.
- Springback was evident in the simulation, however overbend was not modeled into the Draw layout files. It was decided to make changes after draw samples were available in order to build some history for this material.

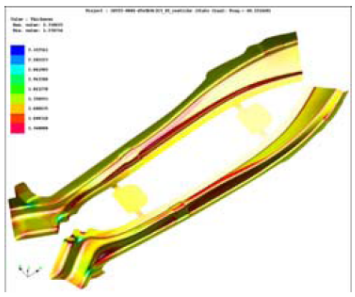
STAGED THICKNESS PLOTS



40 mm off bottom. 32 mm off bottom. 19 mm off bottom.

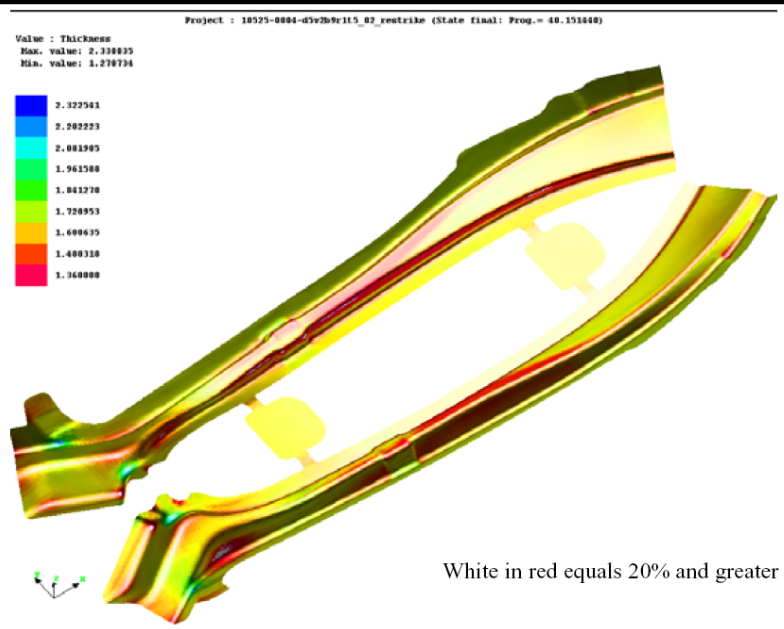


7 mm off bottom.



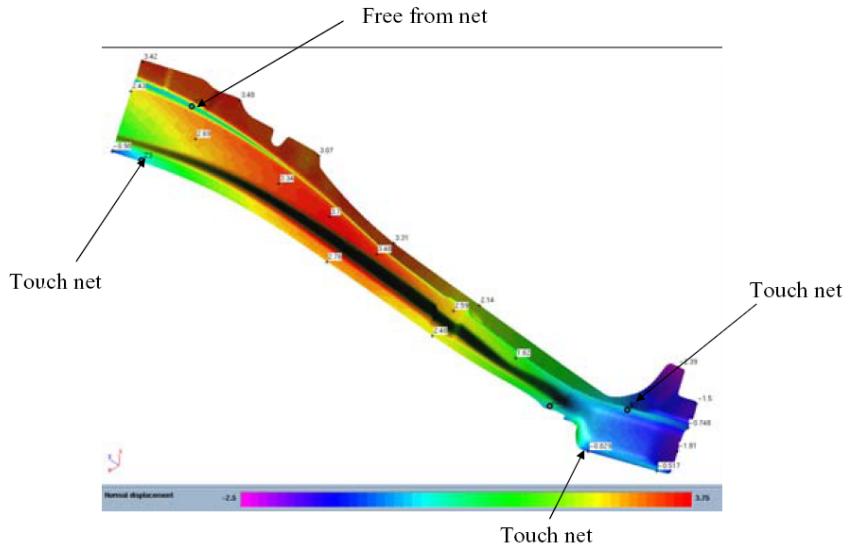
Bottom of stroke.

RESTRIKE FINAL THICKNESS PLOTS



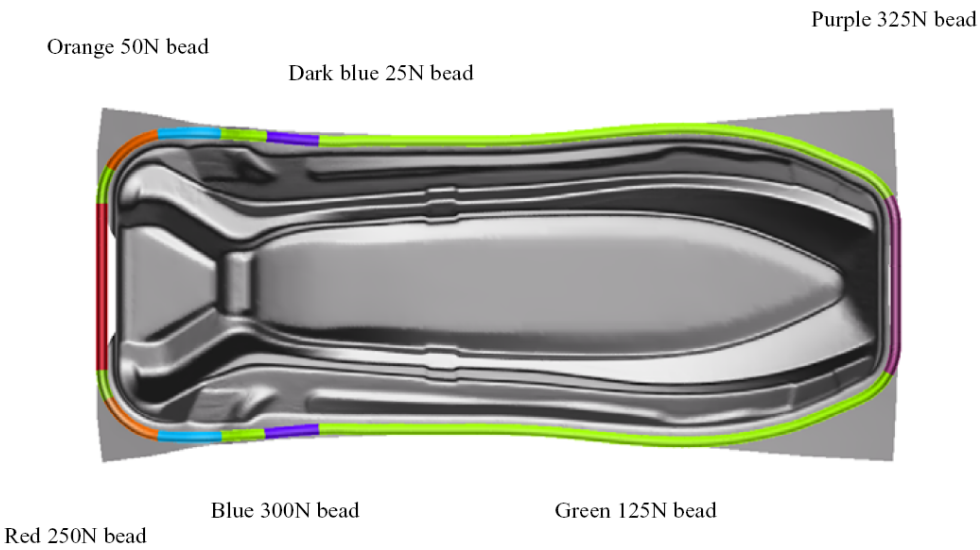
White in red equals 20% and greater thinning.

FREE STATE SPRINGBACK PLOT



DIE CONSTRUCTION & TRYOUT

DRAW BEAD LAYOUT



SPRINGBACK COMPENSATION

Planned approach to controlling springback

- Cut to requested product geometry (original design).
- Recut to revised product geometry to obtain a stable process (remove wrinkling condition).
- Enter revised geometry back into model.
- Morph in model, re-cut to morphed geometry.
- Following slides show actual results.

FINAL SPRINGBACK CONTROL MEASURES

Normal springback controls were not helpful during die tryout:

» Adjusting binder pressure & draw beads in the draw die had marginal effects

» Adjusting tonnage in restrike made no initial difference

» Five recuts were necessary

» Checking fixture was available for tryout

LESSONS LEARNED

DIE TRYOUT

FOLLOW UP ADDITION TO REPORT, MADE AFTER REVIEWING SAMPLES OUT OF TOOLS:

Upon die tryout, it was found that one corner area of draw was fracturing badly and could not be remedied through any fine tuning of the tool. Also a fracture developed in the restrike tool.

A sample of tryout material was sent for analysis. Results were these:

Yield	389 MPa
Tensile	636 MPa
n-value (5 -15%)	0.157
K - value	983 MPa

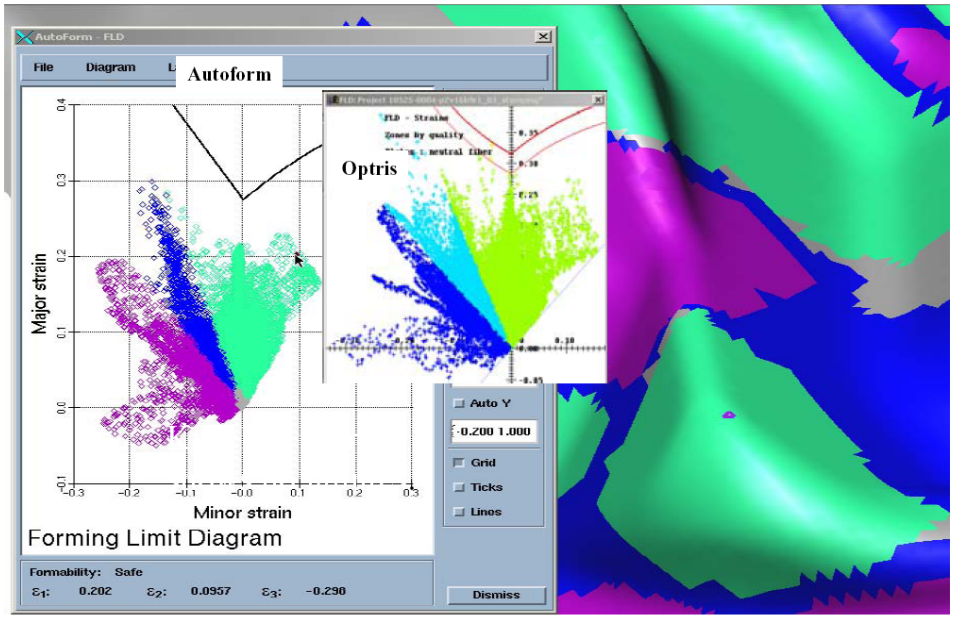
These types of failure mechanisms, on a radius or running in from an edge, are not predicted by the Forming Limit Curve.

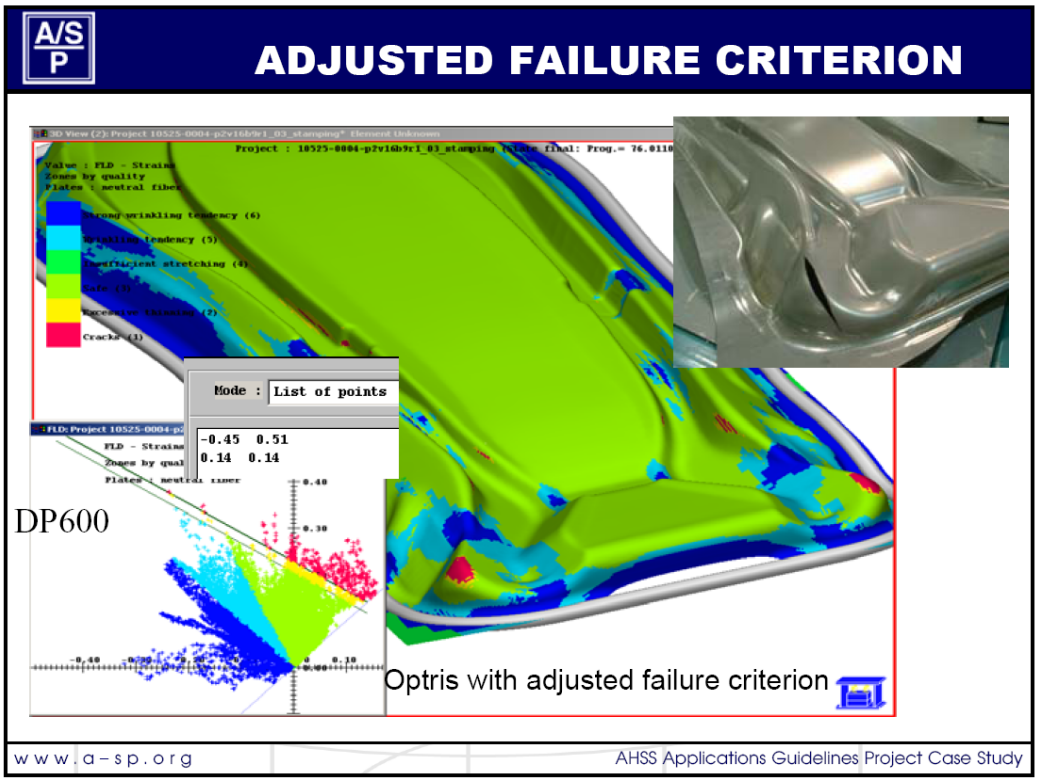
The draw model was remodeled and re-simulated using a failure criterion adjusted to match the real life material forming tendencies as seen from the actual part samples.

Modifications were made within this new model to eliminate the fracture.

DIE TRYOUT

FORMING LIMIT DIAGRAMS




ADJUSTED FAILURE CRITERION
Mode : List of points
-0.45 0.51
0.14 0.14
DP600
Optris with adjusted failure criterion
www.a-sp.org
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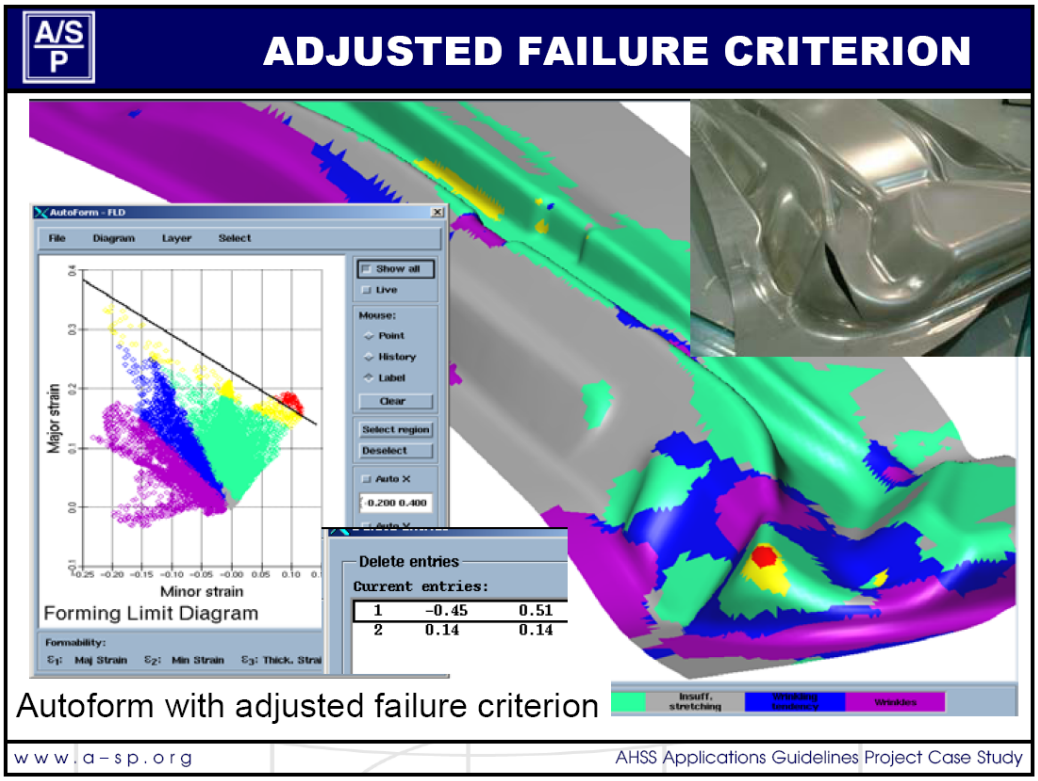
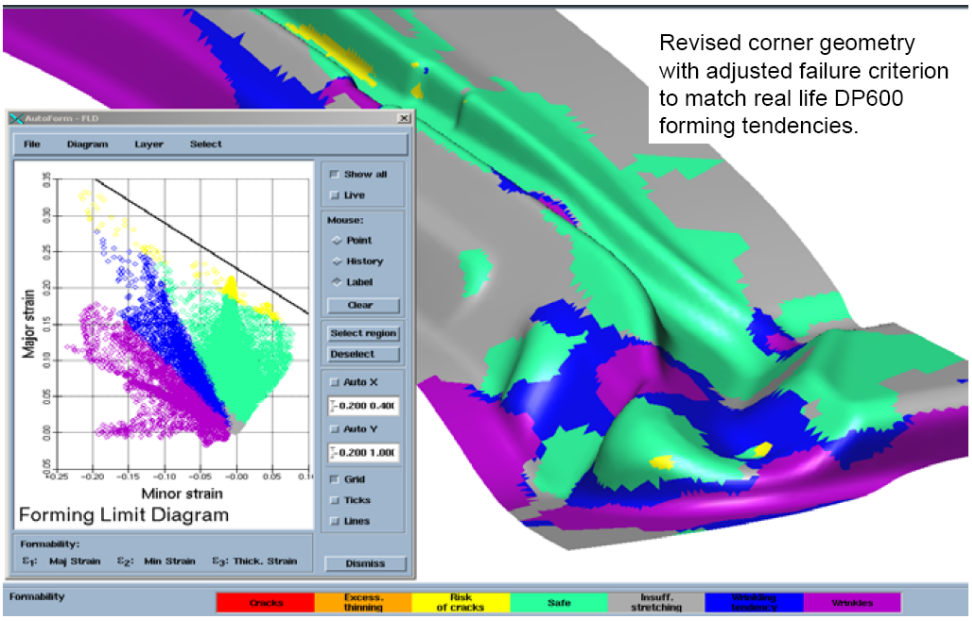
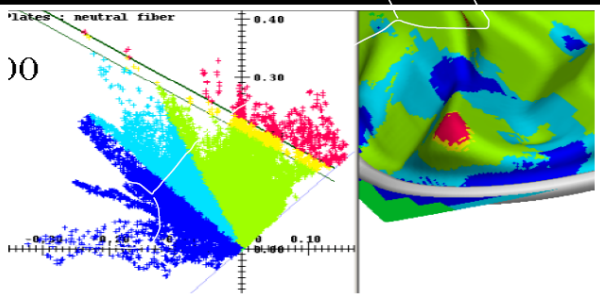

ADJUSTED FAILURE CRITERION
AutoForm - FLD
File
Diagram
Layer
Select
Show all
Live
Mouse:
Point
History
Label
Clear
Select region
Deselect
Major strain
Minor strain
Forming Limit Diagram
Delete entries
Current entries:
1 -0.45 0.51
2 0.14 0.14
Autoform with adjusted failure criterion
www.a-sp.org
AHSS Applications Guidelines Project Case Study

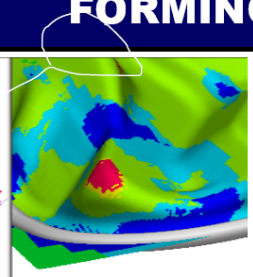
REVISED CORNER GEOMETRY



Revised corner geometry with adjusted failure criterion to match real life DP600 forming tendencies.

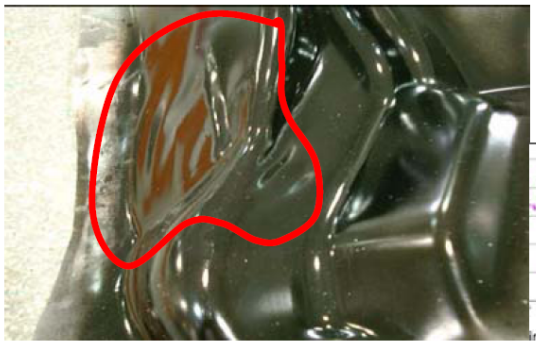
FORMING SIMULATION



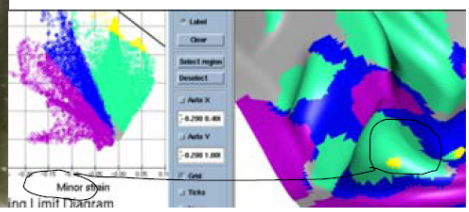


Optris

Severe compression wrinkling was evident in the areas shown.

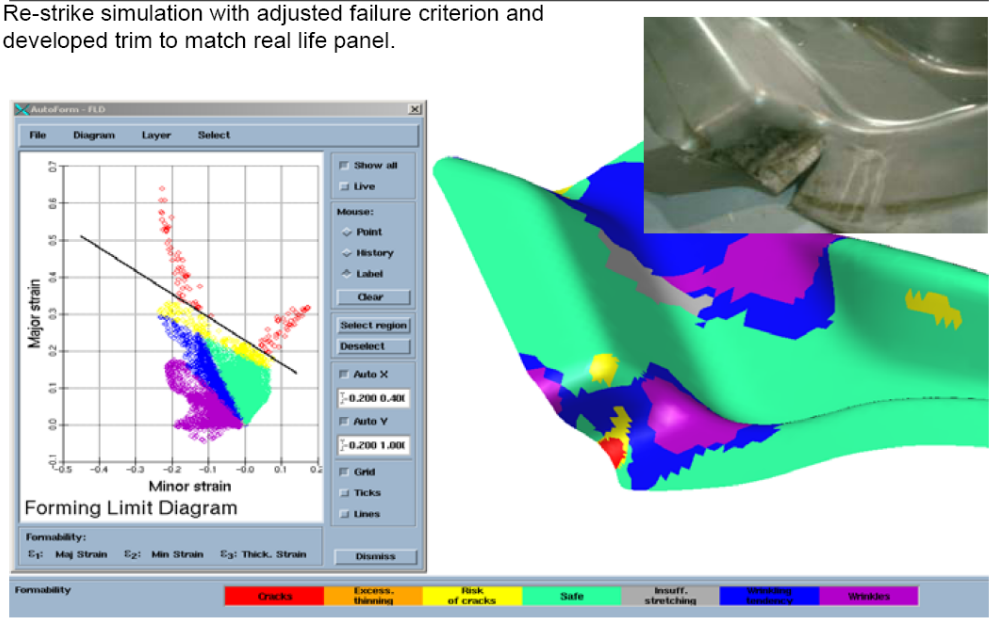


Autoform



RE-STRIKE SIMULATION

Re-strike simulation with adjusted failure criterion and developed trim to match real life panel.



PRODUCTION

PRESS LOAD PREDICTION ACCURACY

Die Stage	Press Loads (Tons)				
	Estimate	CAE Prediction	Actual Measured	Total Available	%
Forming Press Binder	900	740 100	800 60	2000	80
Trim, Pierce	300	N/A	300	1000	30
Cam Trim, Pierce	300	N/A	300	1000	30
Restrike Press Binder	800	N/A 80	800 50	1000	80
Cam Pierce, Separate	300	N/A	300	1000	30

POST-LAUNCH EXPERIENCE

Insights gained during production

- Tool maintenance intervals: 50,000 hits
- Heat buildup issues: Drawing Compound
- Tool wear rates: Form Dies – polish 50,000 hits, weld critical radii 150,000 hits
- Tool breakage problems: Chipped edges – should PM after each run
- Part breakage/springback problems: Minor variation run to run
- Dimensional stability and robustness: Minor part variation run to run but stable within the run
- Steel property variability effects: Splits and necking. Cause of run to run variation
- Die tweaks during production to solve problems: Draw die gage and nitro adjustment. Amount of draw compound. Adjust tonnage and pad pressure in restrike die.

POST-LAUNCH EXPERIENCE

Things done differently next time

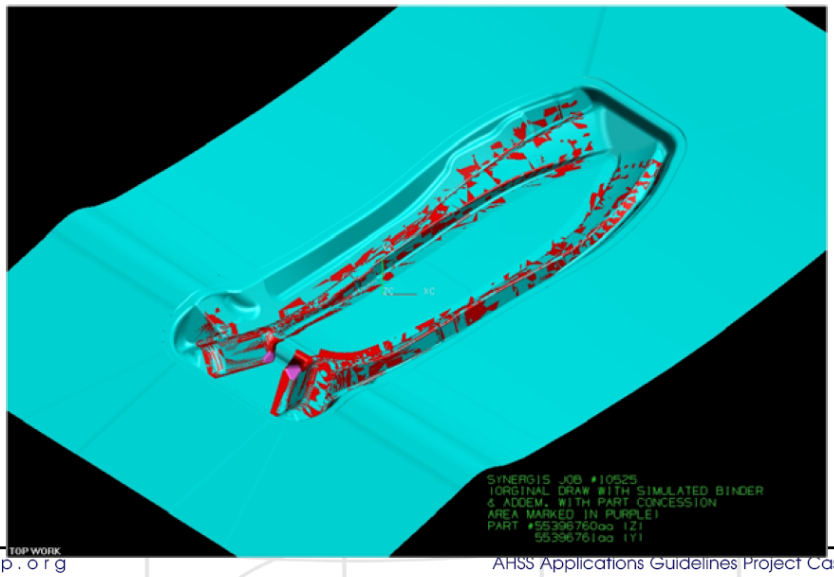
- No knife edge trim conditions – 90 degrees to surface only
- Any unusual shapes or notch trim conditions would be inserts and considered perishable items
- Other than standard types of tool steel would be considered for use in trim applications
- A more robust tool design would be considered

ADDENDA

ADDITIONAL FORMABILITY SLIDES

ADDENDA

ORIGINAL PART W/CONCESSIONS CUT

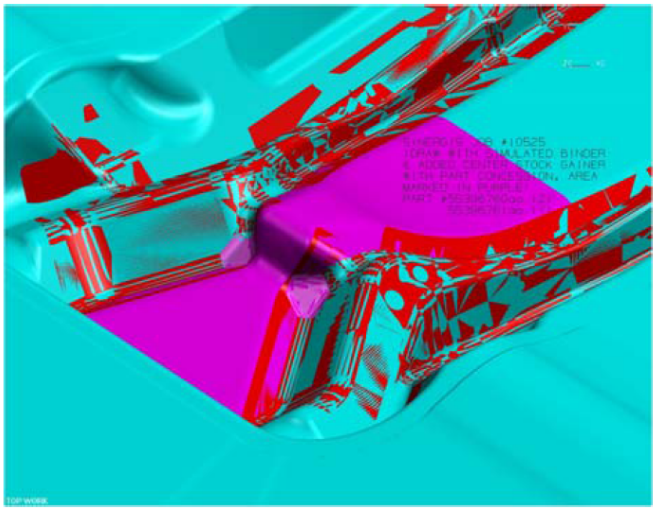


ADDENDA

First Re-cut

Part Concessions

Center stock gainer added

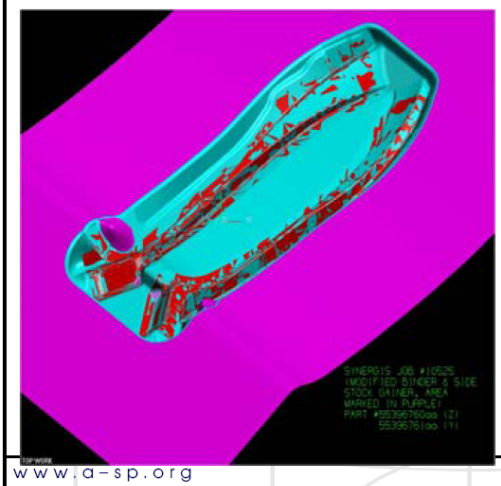


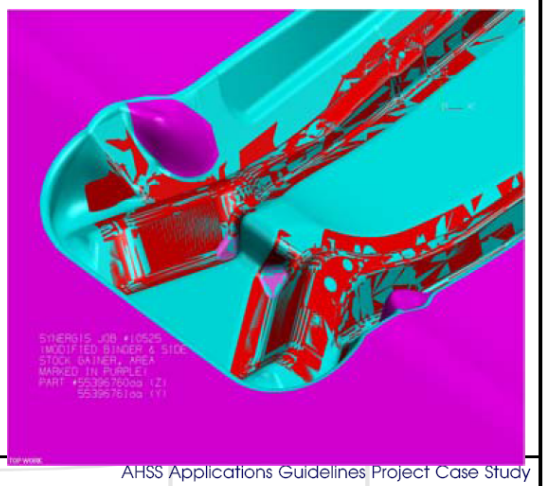
ADDENDA

Second Re-cut

Binder modified

Different side stock gainer





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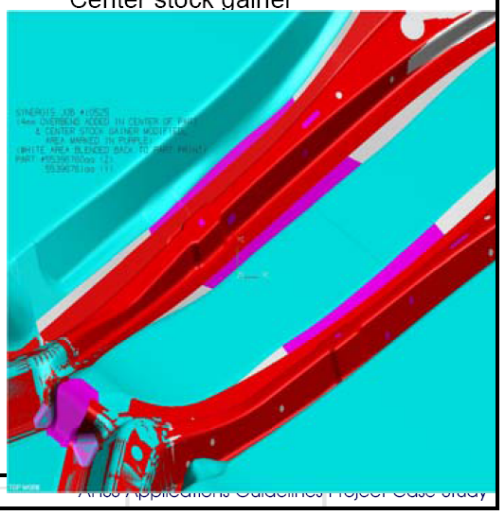
ADDENDA

Third Re-cut

4mm over bend added in center of part, blended back to part over 150mm.

Center stock gainer



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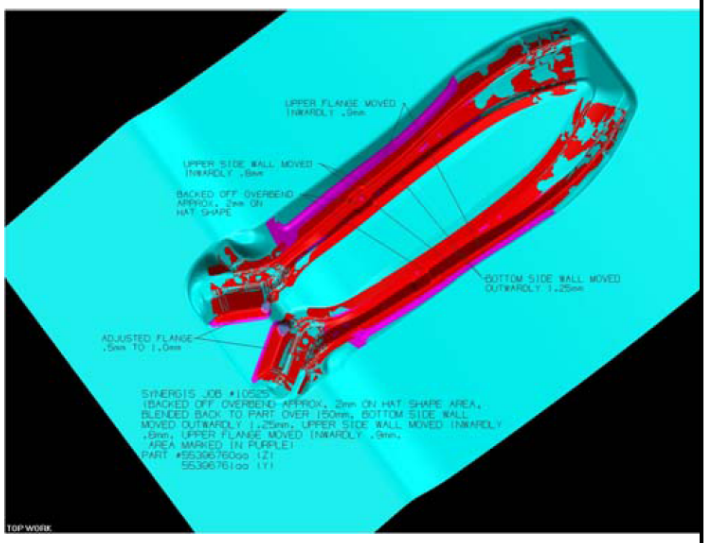
ADDENDA

Fourth Re-cut

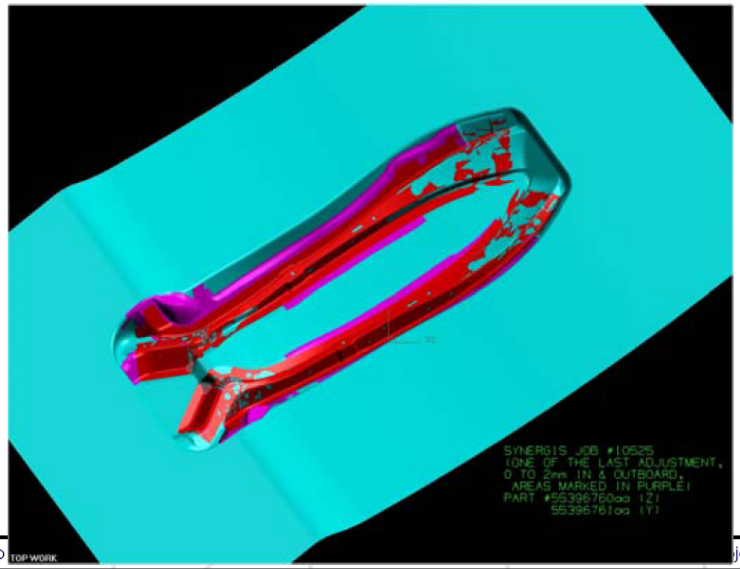
- Backed off over bend approx. 2mm on hat shape area.
- Bottom side wall moved outward 1.25mm.
- Upper side wall moved inward .8mm
- Upper flange moved inward .9mm



ADDENDA

Fifth Re-cut

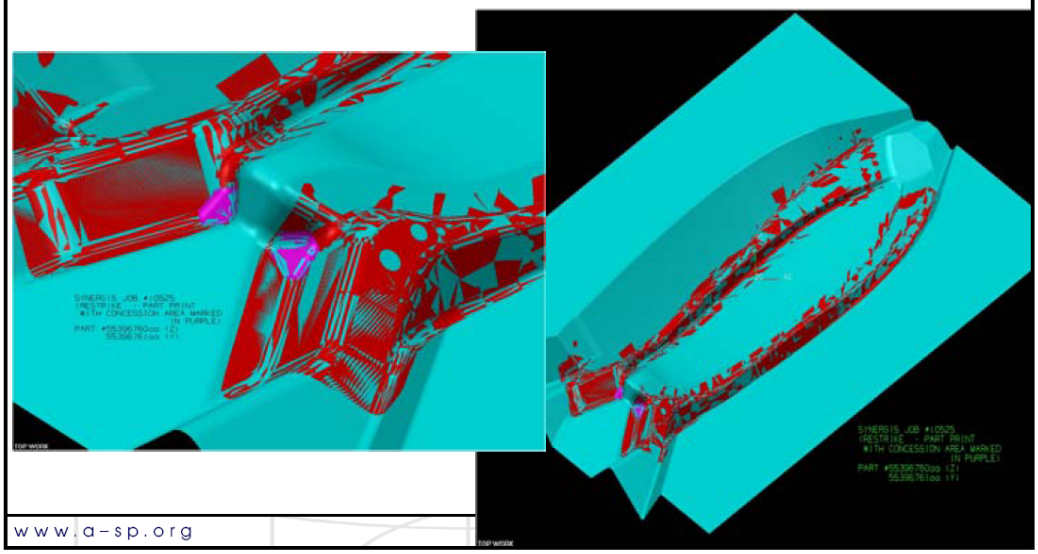
Adjust flanges inboard and outboard approximately zero to 2mm



ADDENDA

Restrike 1 cut only

Restrike, cut to part print with concessions.



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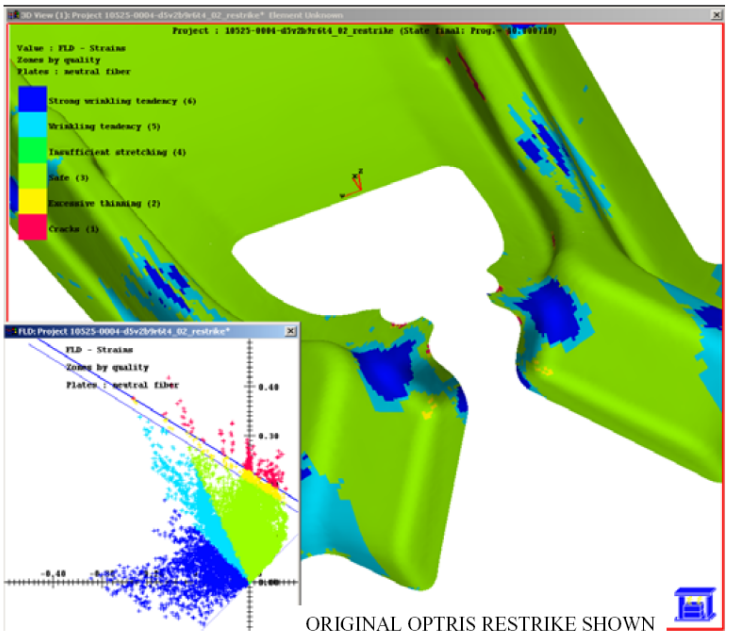
ADDENDA



ORIGINAL OPTRIS RESTRIKE SHOWN WITH CALIBRATED FLC.

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Case Study Summary #6

Part Name	Reinf. - A Pillar Rear Upper	**Material/Grade :**	DP 350/600	**Thickness:**	1.70 mm
Coating :	HD Galvanneal 40A40A	**URL for Full Case Study:**	www.a-sp.org/publications.htm		

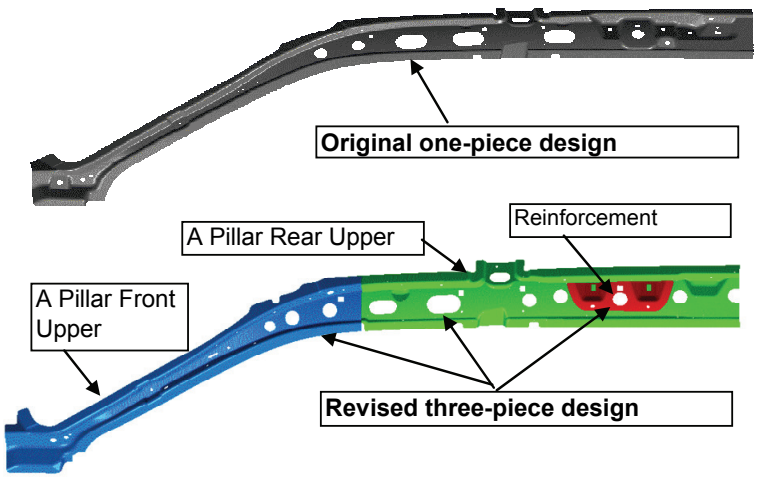
Spring-back/Twist Countermeasures: Cut draw die with adjustment for sprgbk. Adjust binder pressure & re-strike tonnage.

Manufacturing Process

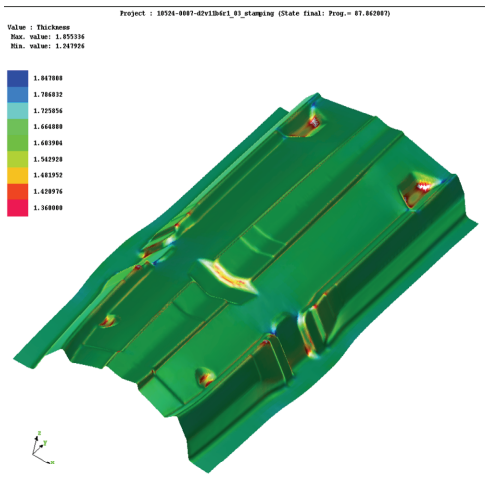
No. of Dies- 5	Double Draw	Trim, Prc.,Cam Prc.	Cam Trim & Prc.	Cam Pierce	Re-Strike & Separate		

Diagrams / Illustrations

Part Geometry

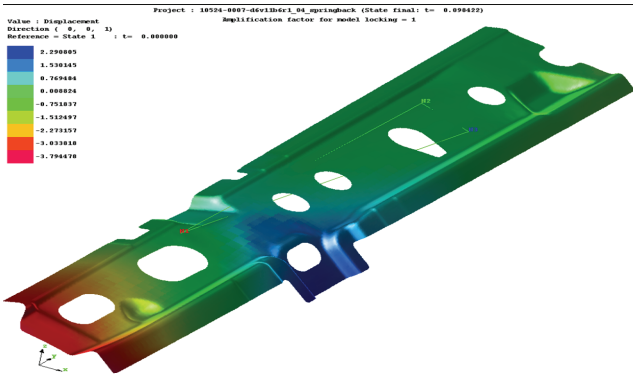


Formability Study



Double Drawn Stamping

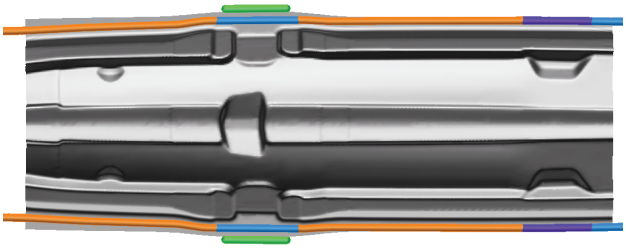
Die Construction Considerations



Springback Plot

Orange 325 N

Dk Blue150 N



Blue 300 N
Green 200 N

Stamping requires varied restraint forces.

Draw Bead Layout

Product Design Notes

Original 1-pc. design split up for DP 600 stamping requirements.
3 x metal thickness minimum radii for this material.
Radii increased in depressions.
Sidewall ribs helped control springback.

Die Construction and Tryout Information

Draw die compensation should be finalized to a die trimmed panel.
Avoid trimming more than 10° from square to surface.
Upgrade all tool steels subject to abrasive wear.
Bottom all form die pads.
Provide a robust die construction.

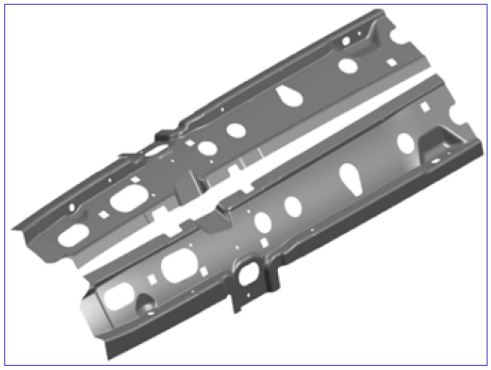
CASE STUDY: #6
REINF.– A-PILLAR REAR UPPER – R&L

Kerry Fitzgerald
AZ Automotive Corp.
AZautomotive.com
kfitzgerald@azautomotive.com

PART DESCRIPTION

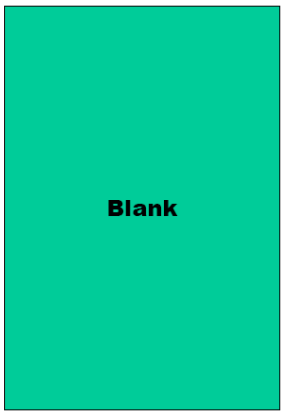
Part Name: REINF-A-PILLAR RR. UPPER

- Mating surfaces and critical features:
  - -Flanges on both sides and upper end.
- Critical radii: – Around pocket
- Depth of draw: – 87mm
- Part features for dimensional stability:
  - -Rib lines



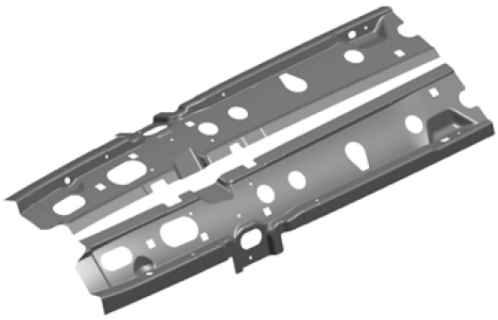
MATERIAL DESCRIPTION

Steel Grade:	DP 600 (350/600)
Coating:	Hot Dip Galvanneal
Gauge:	1.70 mm
Blank Width:	1041 mm
Blank Pitch:	476 mm
Blank Shape:	Rectangle
Lube:	Fuchs Draw Compound



Same steel vendor was used for die tryout and production steel supply.

MATERIAL PROPERTIES



Material Properties (metric):

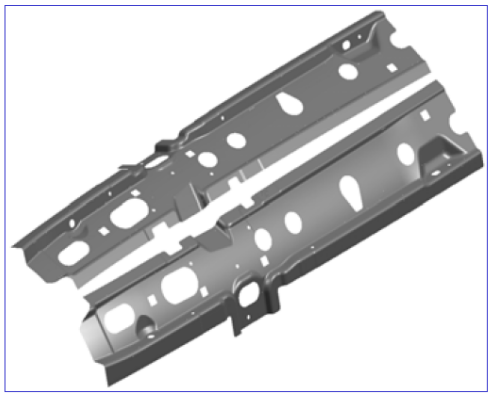
Mat'l:	DP600
Mat'l Thickness:	1.7 mm
Yield:	390 MPa
Tensile:	590 MPa
n-value: (strain range n.a.)	0.169
r-value:	0.89
K-value:	990 MPa

PART HISTORY

NEGOTIATED GEOMETRY CONCESSIONS

Geometry concessions were needed to solve forming and springback issues:

- Radii
- Depth of draw
- Location of features:
  - Removed pocket
  - Split original panel into three parts



ORIGINAL ONE PIECE DESIGN

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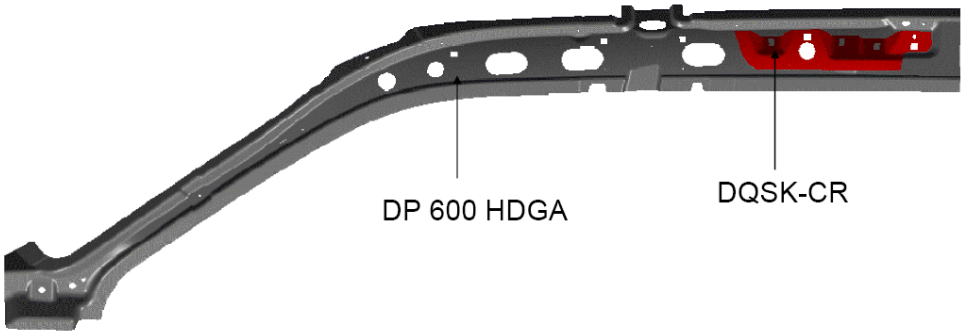
PROPOSED TWO PIECE DESIGN



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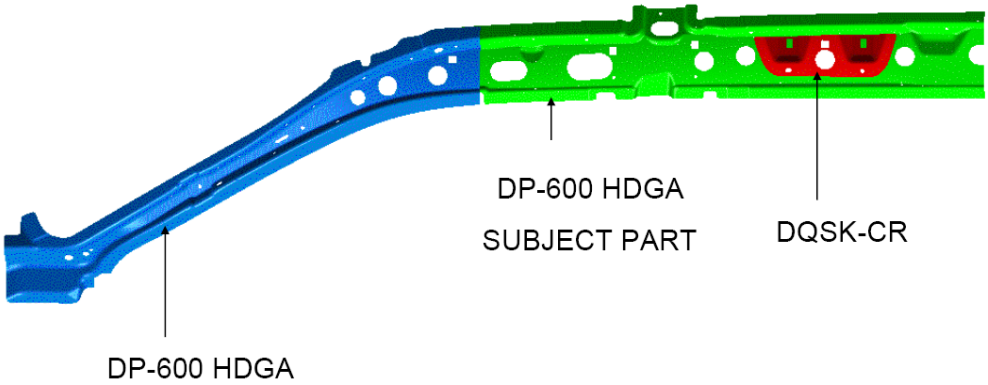
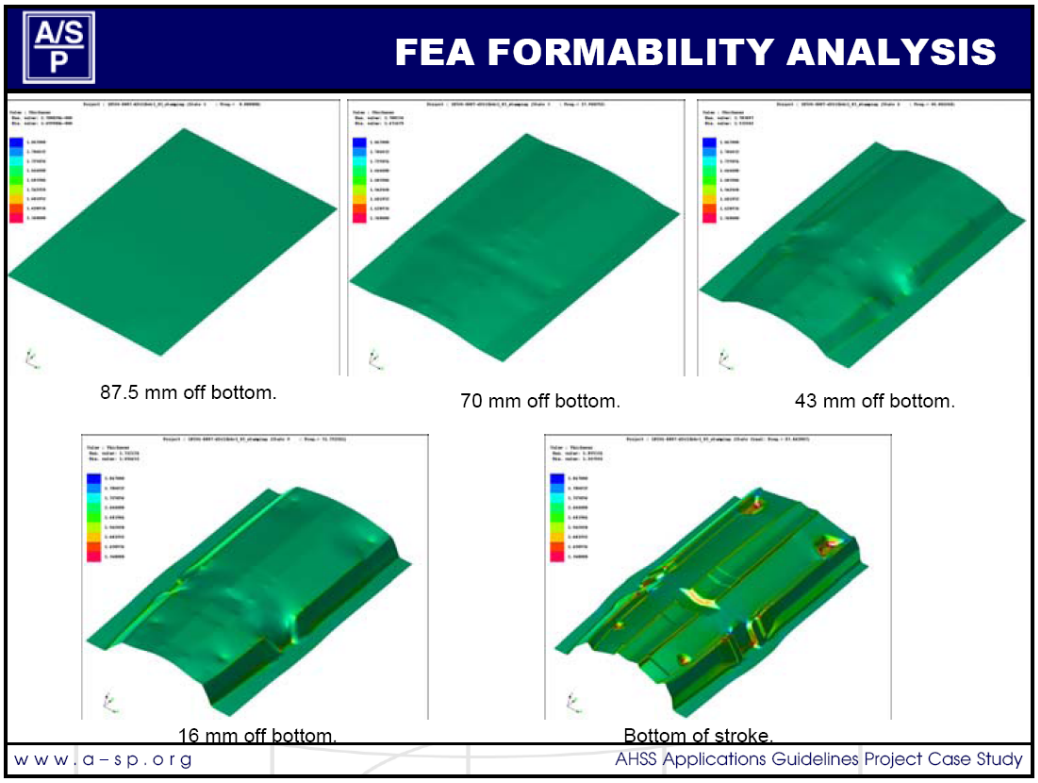
CURRENT THREE PIECE DESIGN



FEA FORMABILITY ANALYSIS


FEA FORMABILITY ANALYSIS
87.5 mm off bottom.
70 mm off bottom.
43 mm off bottom.
16 mm off bottom.
Bottom of stroke.
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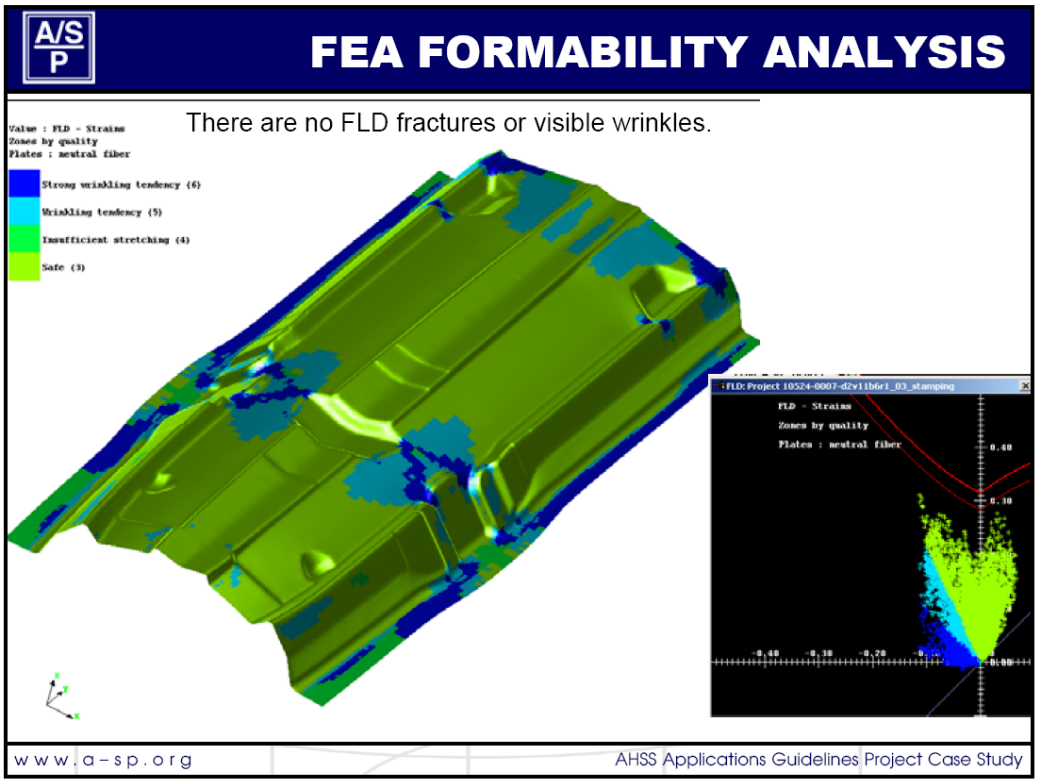
FEA FORMABILITY ANALYSIS
There are no FLD fractures or visible wrinkles.
Value : FLD - Strains
Zones by quality
Plates : neutral fiber
Strong wrinkling tendency (6)
Wrinkling tendency (5)
Insufficient stretching (4)
Safe (3)
FLD: Project 10524-0007-d2v11b6r1_03_stamping
FLD - Strains
Zones by quality
Plates : neutral fiber
0.40
0.30
-0.40
-0.30
-0.20
0.00
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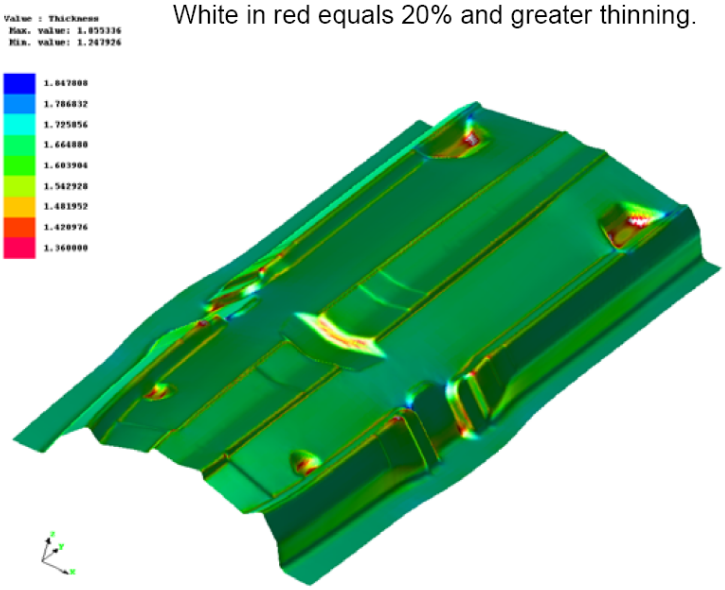
FEA FORMABILITY ANALYSIS

White in red equals 20% and greater thinning.



FEA FORMABILITY ANALYSIS

FEA formability study results were very similar to what was experienced in die tryout.

DIE PROCESSING

PRESS LINE CONSTRAINTS

Press line assigned to this part.

Press #1: Type	Muller (Hyd)	Bed size	158 x 94	Press tonnage	2000
Press #2: Type	Verson (Mech)	Bed size	102 x 72	Press tonnage	1000
Press #3: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #4: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #5: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000

Target production rate - 375 / hr

Die-applied nitrogen cushion pressure in draw die.

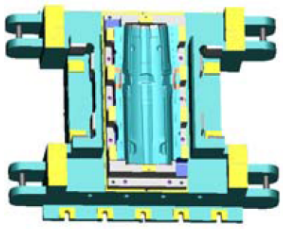
STAMPING PROCESS DESIGN

Process Flowchart:

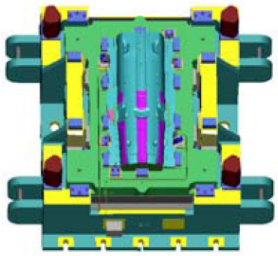
Blank	Wash & Lube	Forming Operation	Second Operation	Third Operation	Fourth Operation	Fifth Operation
Straight sheared rectangular blank	Roll Coat	Draw	Trim, Pierce, Cam Pierce	Cam Trim & Pierce	Cam Pierce	Restrike & Separate

STAMPING PROCESS DESIGN

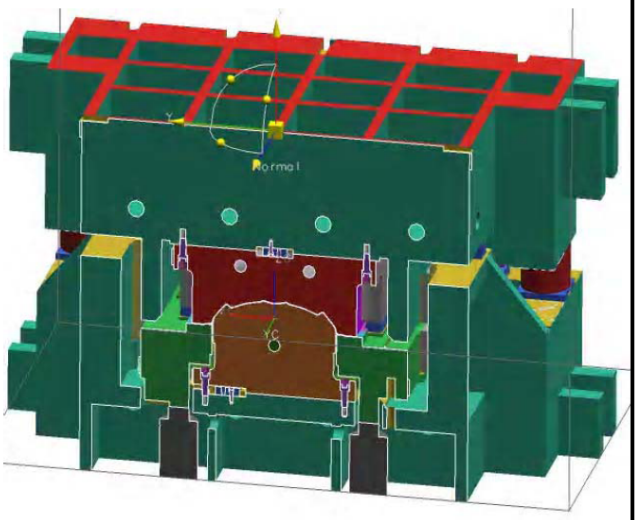
First Die Operation



Upper

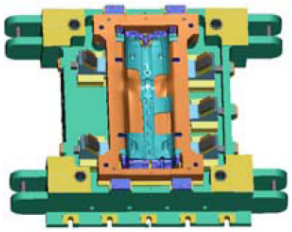


Lower

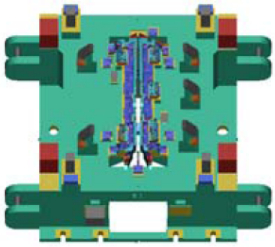


STAMPING PROCESS DESIGN

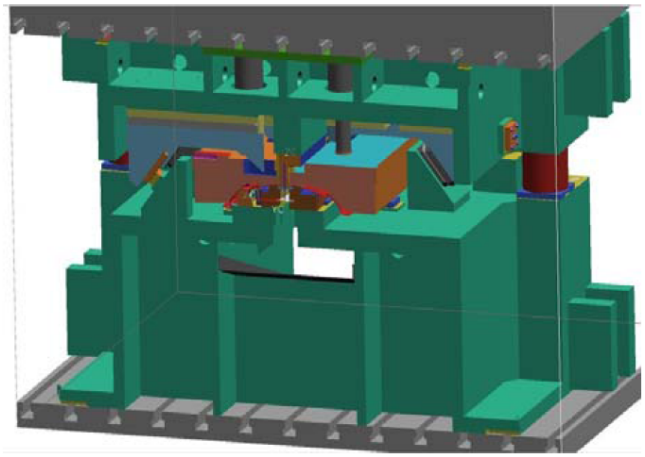
Second Die Operation



Upper



Lower



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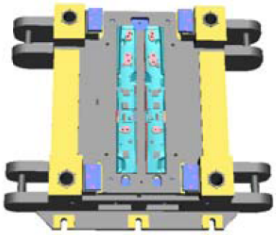
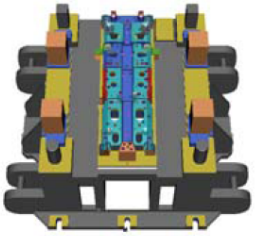
STAMPING PROCESS DESIGN

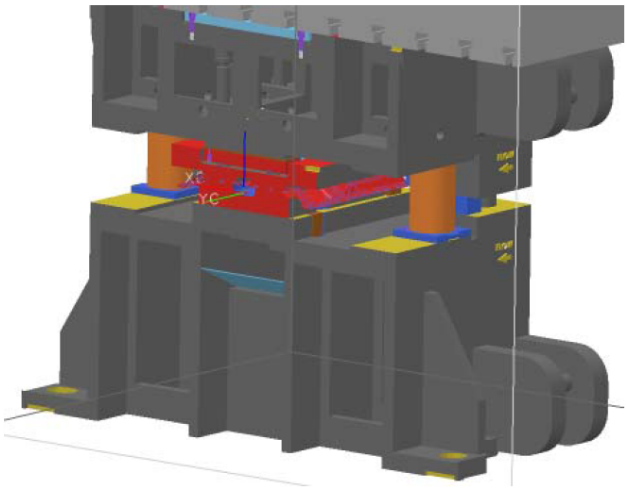
Third Die Operation



Upper



Lower



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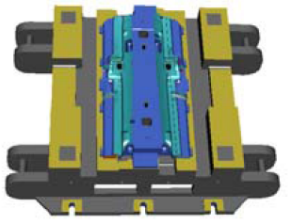
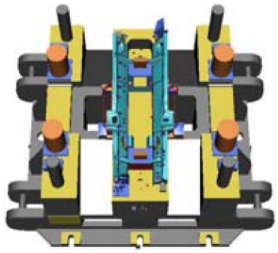
STAMPING PROCESS DESIGN

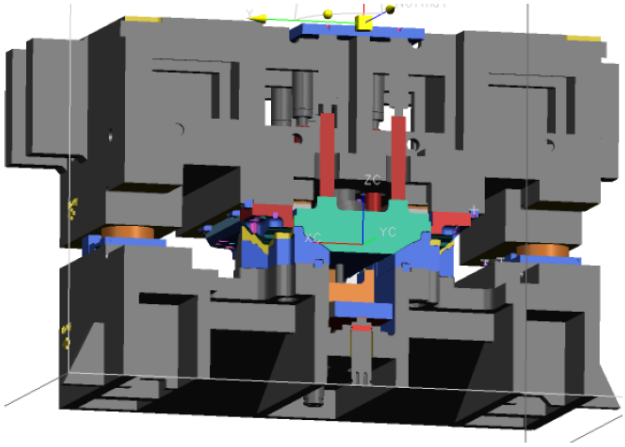
Fourth Die Operation



Upper



Lower



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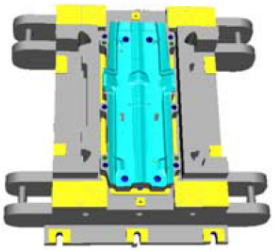
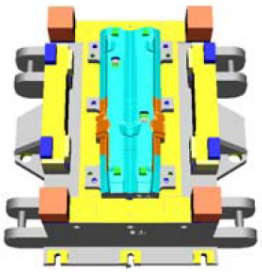
STAMPING PROCESS DESIGN

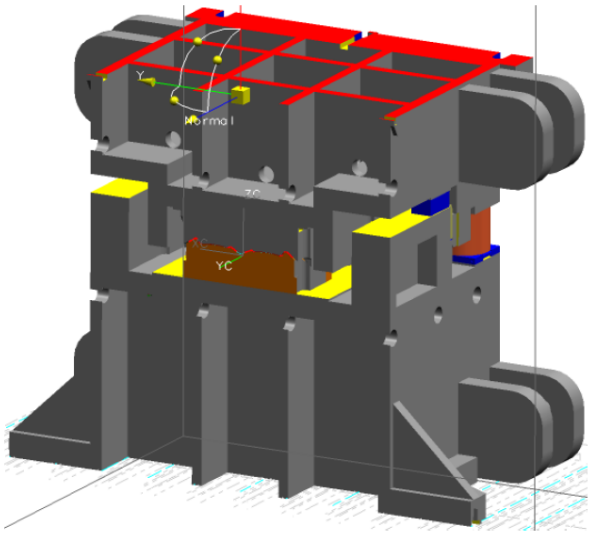
Fifth Die Operation



Upper



Lower



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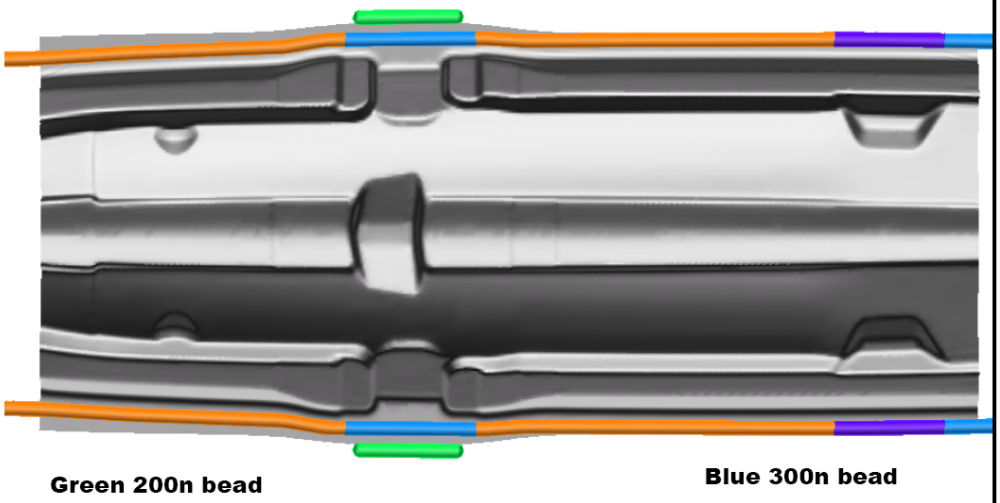
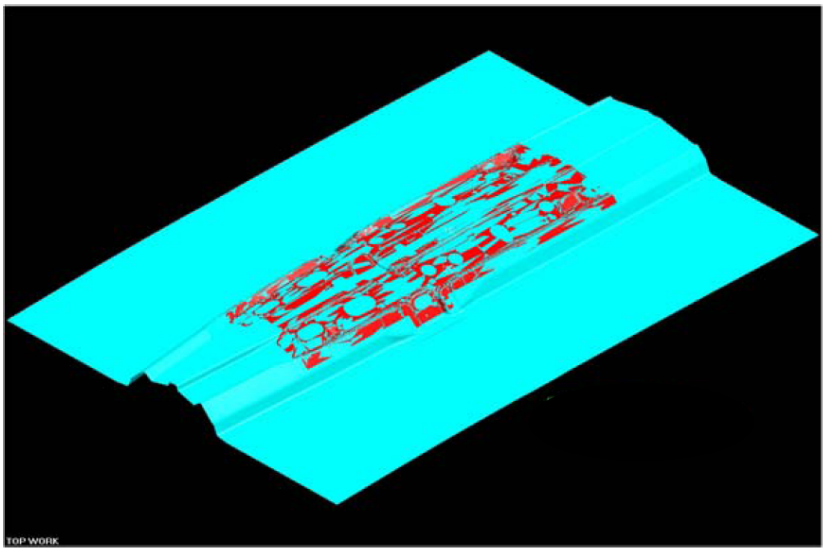
DIE CONSTRUCTION & TRYOUT

DRAW BEAD LAYOUT



SIMULATION RESULTS

Draw die cut to original part print and simulated data results.



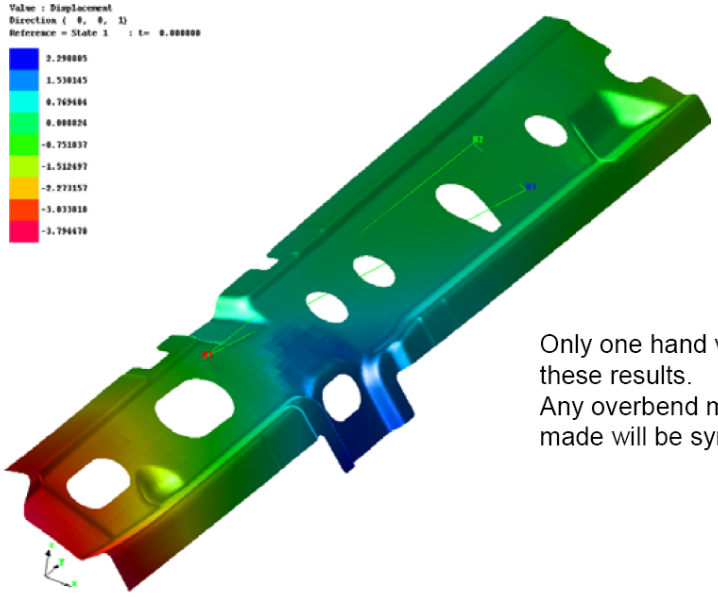
SPRINGBACK COMPENSATION

Approach to controlling springback

- Cut to nominal and re-cut to control
- Cut to nominal, morph in model, re-cut to morphed geometry

See following slides

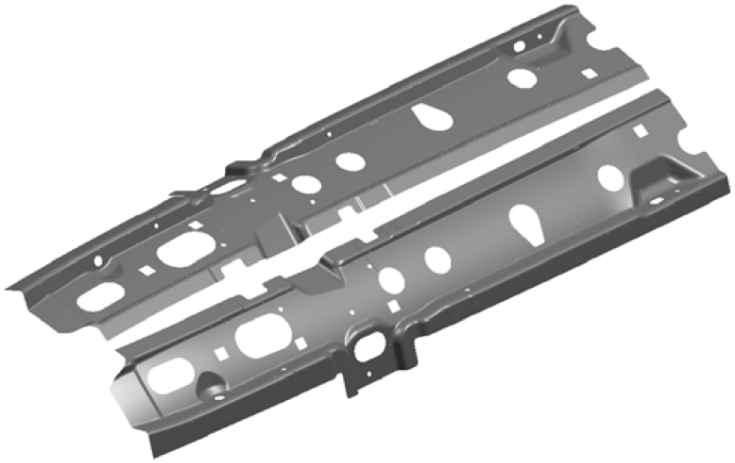
SPRINGBACK PLOT



Only one hand was locked for these results.
Any overbend moves made will be symmetrical.

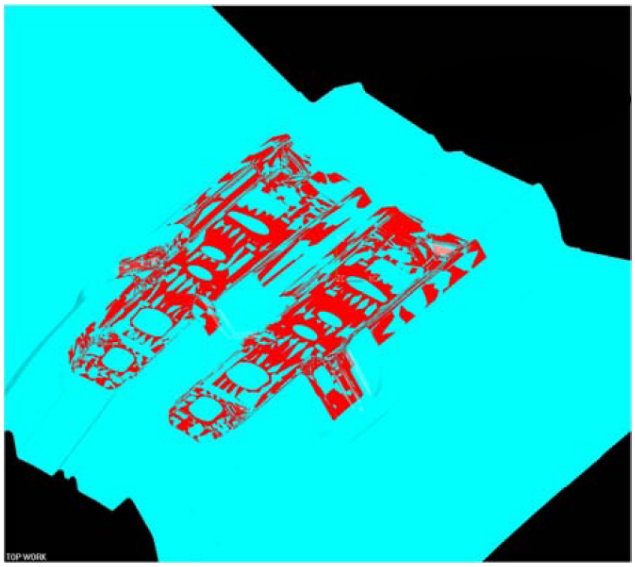
SPRINGBACK

Springback and overbend were not modeled into the Draw layout files. Changes were made after draw samples to build history on this new material.



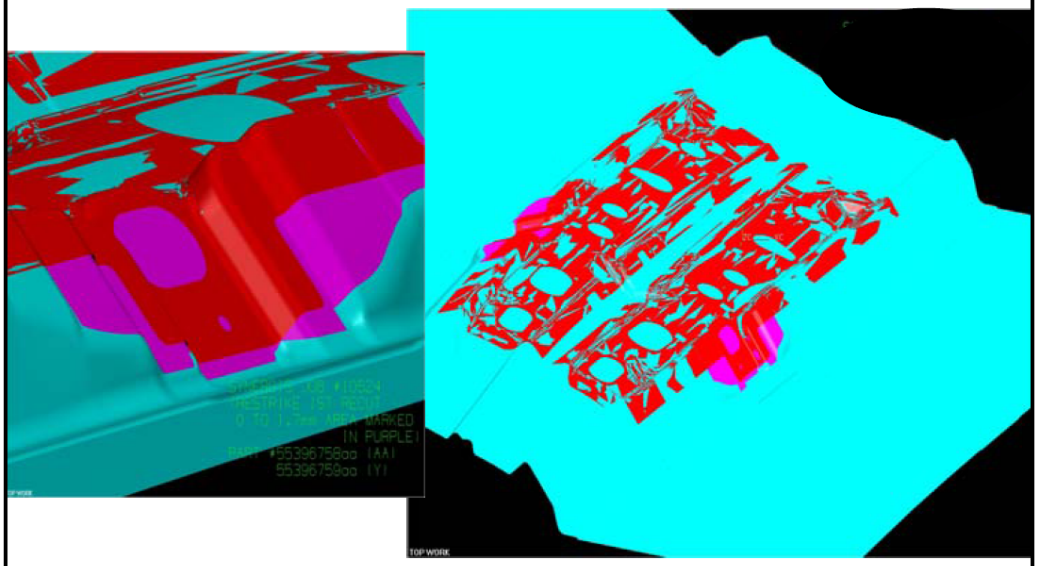
RE-STRIKE DIE

Original data was cut to part print and simulated data.



RE-STRIKE DIE

Re-cut center T shape area from zero to 1.7mm



FINAL SPRINGBACK CONTROL MEASURES

Springback controls employed successfully during die tryout:

» Adjusting binder pressure in draw

» Adjusting tonnage in re-strike

Checking fixture was available for die tryout

LESSONS LEARNED

Insights gained during die tryout

- Run dies at production rate during tryout
- Tryout in similar press (Mechanical, Hydraulic)
- Flange prior to final trim on stretch flanges to avoid edge cracking
- Target trimming at 90 degrees to surface; avoid trimming more than 10 degrees from vertical to surface. Standard trim clearances apply.
- Use inserts for flange and radii adjustments to facilitate tryout geometry changes.

PRODUCTION

PRESS LOAD PREDICTION ACCURACY

Die Stage	Press Loads (Tons)				
	Estimate	CAE Prediction	Actual Measured	Total Available	%
Forming Press Binder	1500	740 60	702 60	2000	35
Trim, Pierce	500	N/A	250	1000	25
Cam Trim, Pierce	500	N/A	250	1000	25
Cam Pierce	500	N/A	250	1000	25
Re-strike, Separate	700	N/A	600	1000	60

POST-LAUNCH EXPERIENCE

Insights gained during production

- Tool maintenance intervals: 50,000 hits.
- Heat buildup issues: None.
- Tool wear rates: Form Dies – polish after 50,000 hits, weld critical radii after 150,000 hits.
- Tool breakage problems: Chipped edges – should PM after each run.
- Part breakage/springback problems: Minor variation run to run compensated by pressure changes.
- Dimensional stability and robustness: Minor part variation run to run but stable within the run.
- Steel property variability effects: Splits and necking. Cause of run to run variation.
- Die tweaks during production to solve problems: Draw die gage and nitro adjustment. Amount of draw compound. Adjust tonnage in restrike die. (All standard adjustments)

POST-LAUNCH EXPERIENCE

Things done differently next time

- No knife edge trim conditions – 90 degrees to surface only.
- Any unusual shapes or notch trim conditions would be inserts and considered perishable items. Trim steels with greater shock resistance should be considered.
- Other than standard types of tool steel would be considered for use in trim applications.
- A more robust tool structural design would be considered.

LESSONS LEARNED

Overall Insights Gained – Product Design

- Avoid abrupt geometry changes.
  Inhibits metal flow causing splits. Embossment sidewalls should be kept to around 45 degrees to facilitate metal flow.
- Part should be designed open-ended to minimize forming problems.
- Product feature radii should be greater than 3x thickness with DP600.
- Minimize stretch and compressions flanges as much as possible.

LESSONS LEARNED

Overall Insights Gained – Draw Die

- Use hard welds for draw beads and die radii – typically one material grade up.
  PM intervals must be reduced – 50,000 hit intervals
- Equalize depth of draw as much as possible to minimize residual stress gradients – sources of wrinkles and springback/twist
- Hard check fixture still recommended.
- Pressures required to set draw beads and keep binders closed during draw are two to three times greater in DP600 than that for mild steel
- Open end design minimized buckling, provided good dimensional stability robustness in production.
- Run die tryout at production rates to assure production springback is measured and corrected

LESSONS LEARNED

Overall Insights Gained – Blanking, Trimming, Piercing Dies

- Higher DP600 strength required material upgrade (at least one grade up in shock resistance) for trim steels, dies, punches.
- Piercings <2 mm should be 90 degrees to surface; piercings >2 mm should be 10 degrees max. to surface.
- Trim angles should be 90 degrees to surface.
- Unusual shapes or notch trim conditions should be easily-replaced inserts and considered perishable.

LESSONS LEARNED

Overall Insights Gained – Restrike Dies

- Do not rely on restrike to move previously work hardened material after the initial draw.

  Restrike can be used to coin radii or adjust angles, but it will not effectively change shape. Use restrike to add beads or darts to correct twist or crown or to add local feature embossments.

Case Study Summary #7

Part Name	Reinf.- Ctr. Pillar Otr. Upr.	**Material/Grade :**	DP 550/980	**Thickness:**	1.5mm
Coating :	Uncoated	**URL for Full Case Study:**	www.a-sp.org/publications.htm		

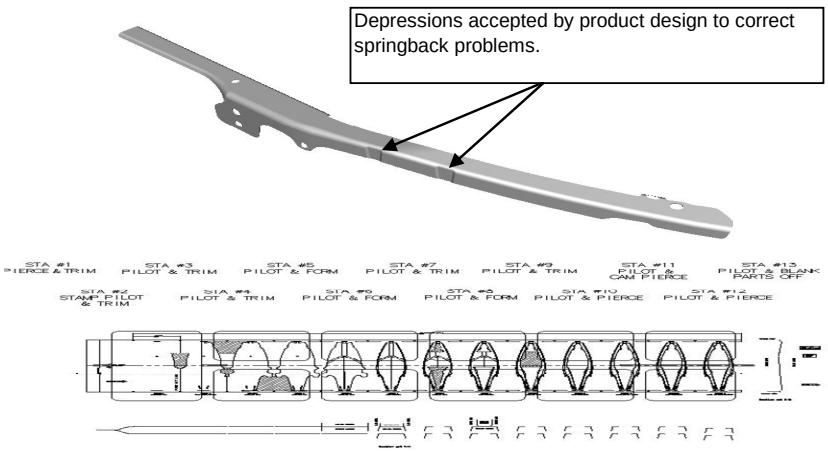
Spring-back/Twist Countermeasures: Overbend, overcrown and added depressions in areas of metal compression.

Manufacturing Process

No. of Dies	**1**	**Prog. Die**					

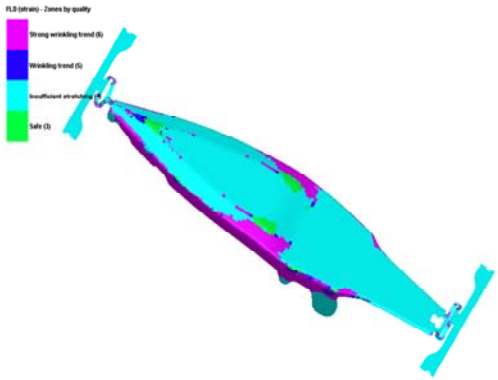
Diagrams / Illustrations

Part Geometry



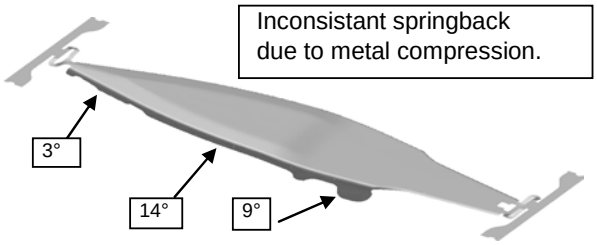
Progression layout - 13 stages

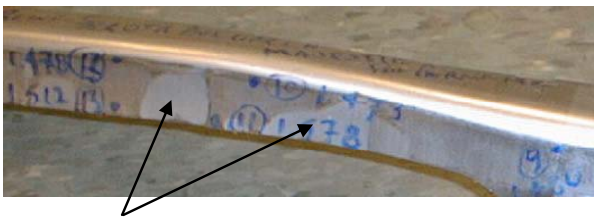
Forming Simulation



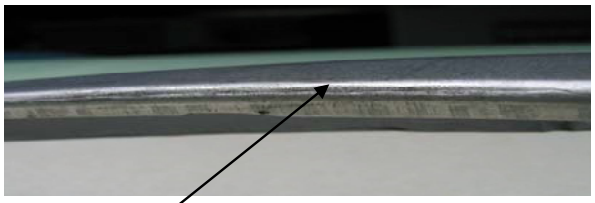
Parts formed R&L Dbl. in a Progressive Die.

Die construction considerations





Waves caused by compressed metal on flange
Overcrown affected flange springback.



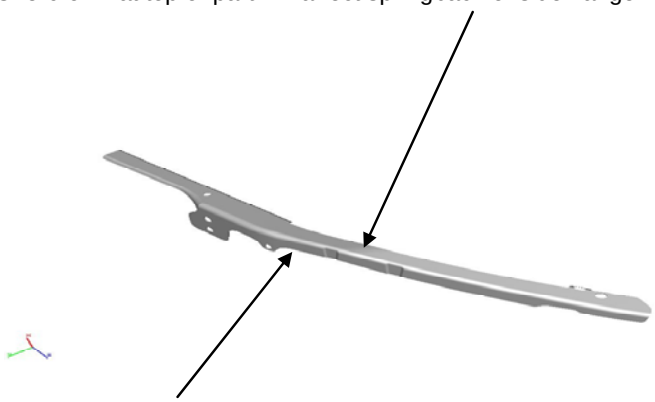
Radius fracture due to small 1T bend radius. 3T required.

Product Design Notes

DP 980 does not compress well. Metal take up depressions should be added when compression exceeds 3%.
3T I/S of metal minimum bend radius required for DP 980.

Die Construction and Tryout Information

Overcrown at top of part will affect springback of side flange.



Provide 15° open wall angle in die setup to allow for springback compensation in the flange die.
Flange steels must be coated. Vanadium Carbide process.
No thermal issues with die running 40 SPM with mill oil lube.
Avoid placing trim by-pass notches in stretch areas of flange.
Robust die sections required with heels and keys for thrust.
Trim square to metal surface wherever possible.

CASE STUDY #7:
REINF.- C-PILLAR OUTER UPPER

Ken Schmid
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Advanced Vehicle Die & Stamping Engineer
General Motors Corporation
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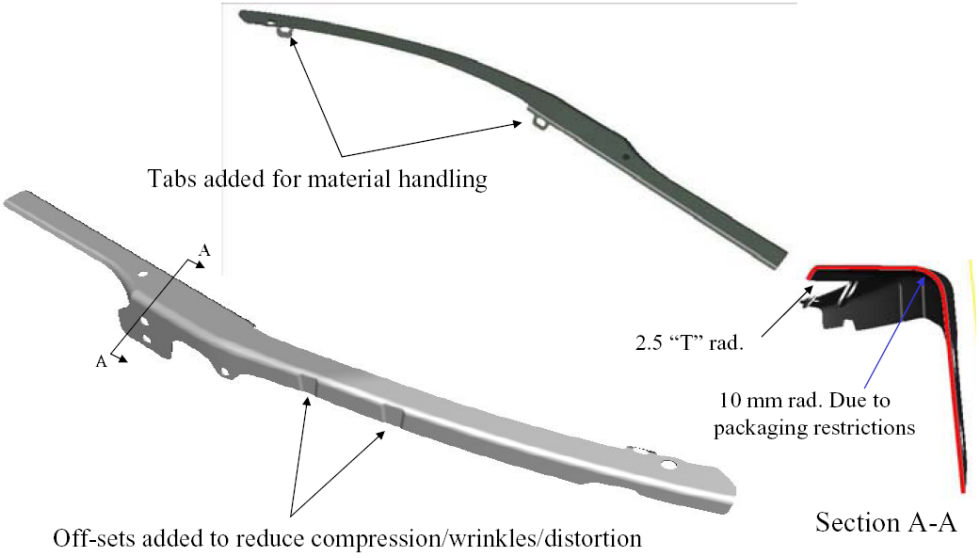
PART DESCRIPTION

Part Name: REINF-C/PLR OTR UPR

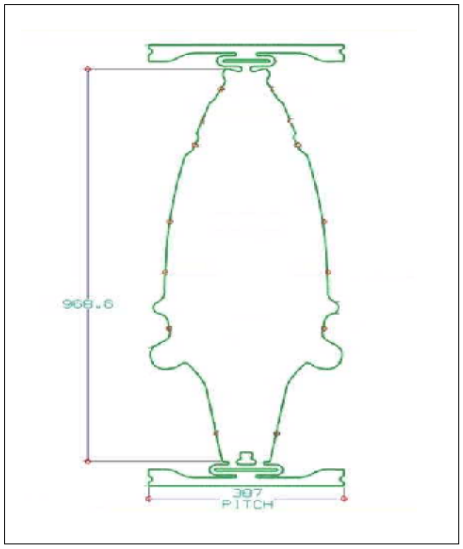


MATERIAL DESCRIPTION

Specification

Steel Grade: DP 980 (550Y/980T) CR
Coating: Bare
Gauge: 1.5 mm
Blank Width: 387 mm
Blank Pitch: 968.6 mm
Blank Shape: Developed
Lubrication: Mill Oil

Blank is for RH & LH part (2 out)



PRESS LINE

Press --- 5500 mm High Speed Progressive Die Press
2000 Ton capacity

Current production rate = 32 spm (Die runs 40 spm, end of line stacking reduces rate to 32 spm)

Part or process factors that led to this press line assignment:

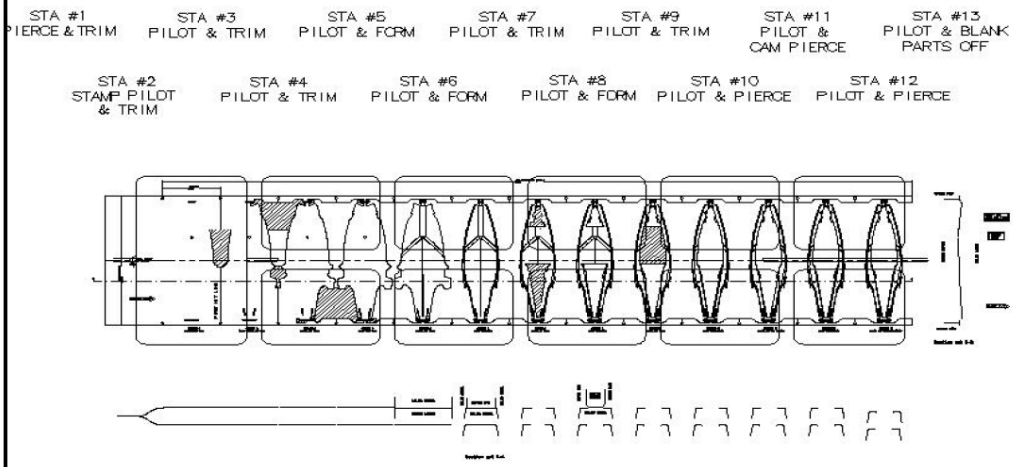
Part & Blank size to run double

STAMPING PROCESS DESIGN

Process Overview

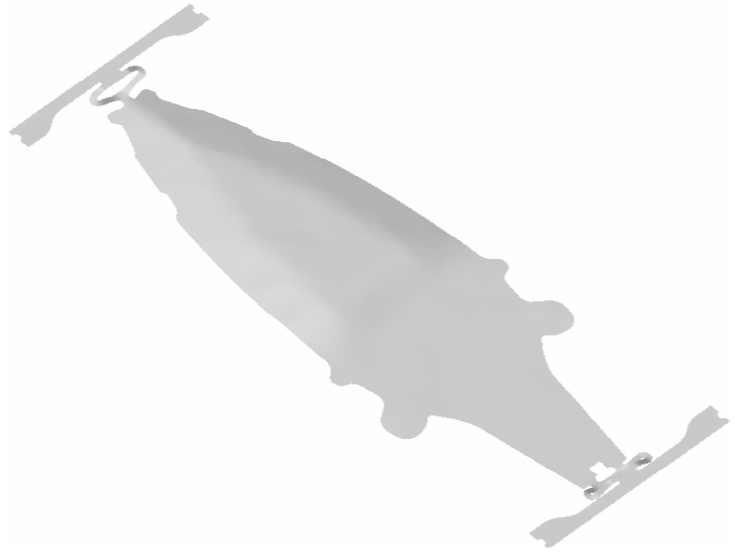
Forming Process Type: Progressive Die Process

Process Flow



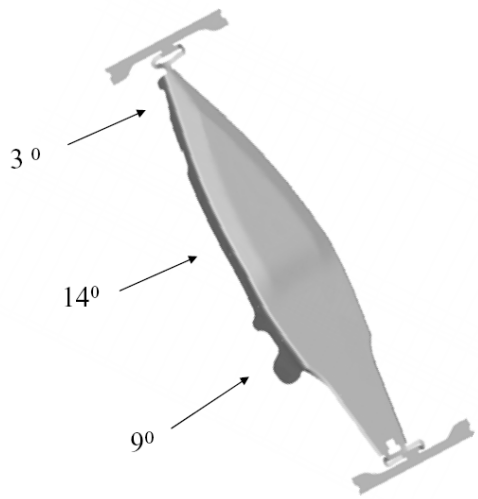
STAMPING PROCESS DESIGN

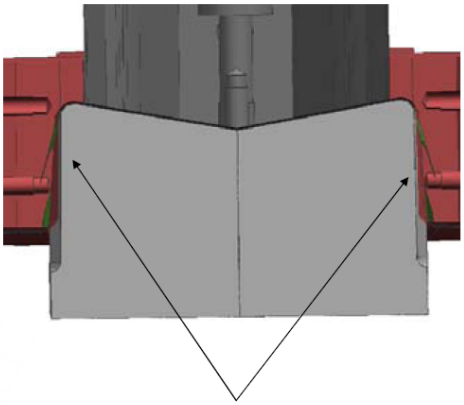
First Forming Operation – Form with Solid Upper and Lower



STAMPING PROCESS DESIGN

Second Forming Operation – Flange Down

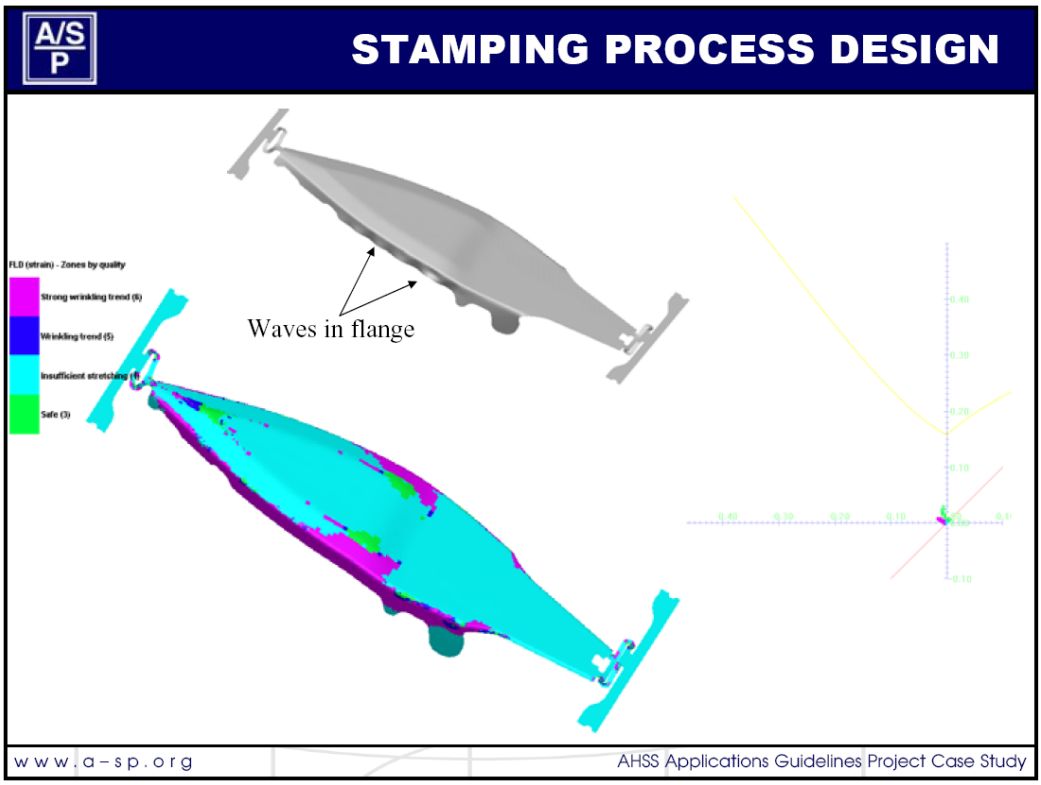




Over-bend compensation varies 3 – 14 degrees along break line

FEA FORMABILITY ANALYSIS

- PamStamp Analysis was used for Formability Simulation
  - No stress/strain failure predicted
  - Compression on flange shown as "Strong Wrinkle Trend"
  - Compression in local corner shown as 20% thickening
- PamStamp Analysis was used for Spring-Back prediction
  - 3 to 14 degrees spring-back predicted along flange
  - 1 mm to 10 mm spring-back predicted along top of part
  - Twist was difficult to determine due to the narrow section


STAMPING PROCESS DESIGN
FLD (strain) - Zones by quality
Strong wrinkling trend (6)
Wrinkling trend (5)
Insufficient stretching (4)
Safe (3)
Waves in flange
www.a-sp.org
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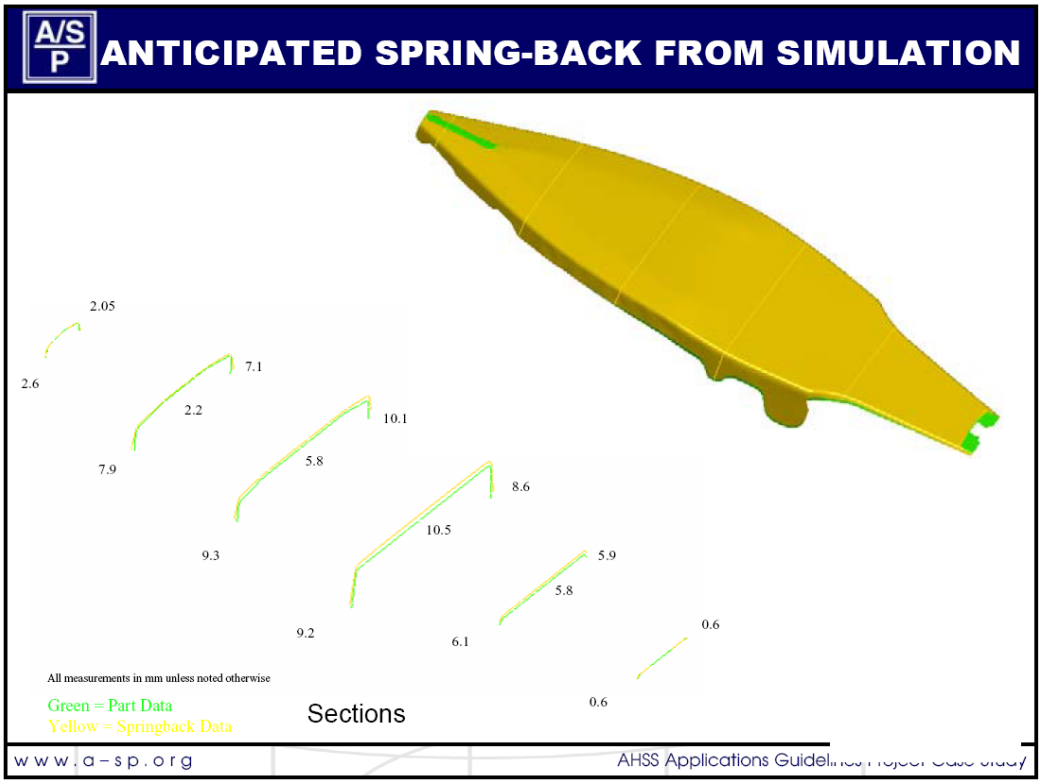
ANTICIPATED SPRING-BACK FROM SIMULATION
2.05
2.6
7.1
2.2
10.1
7.9
5.8
8.6
10.5
9.3
5.9
5.8
9.2
6.1
0.6
0.6
All measurements in mm unless noted otherwise
Green = Part Data
Yellow = Springback Data
Sections
www.a-sp.org
AHSS Applications Guidel

STAMPING PROCESS DESIGN

Waves in flange caused by compression

Forming was inconsistent

Over crown effected flange spring-back

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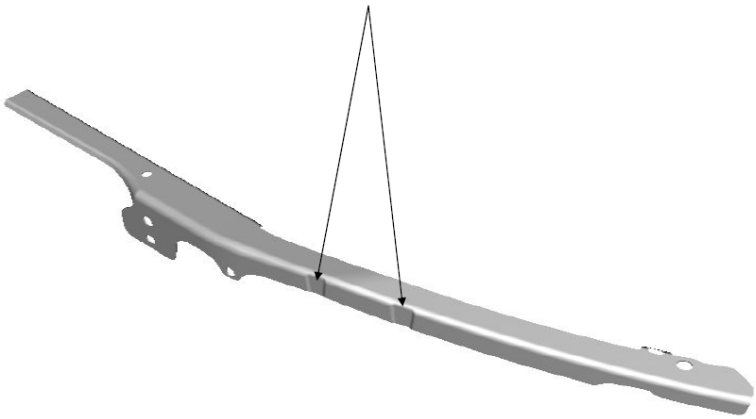
NEGOTIATED GEOMETRY CONCESSIONS

Geometry concessions needed to solve compression & spring-back problems that were accepted by Product Design



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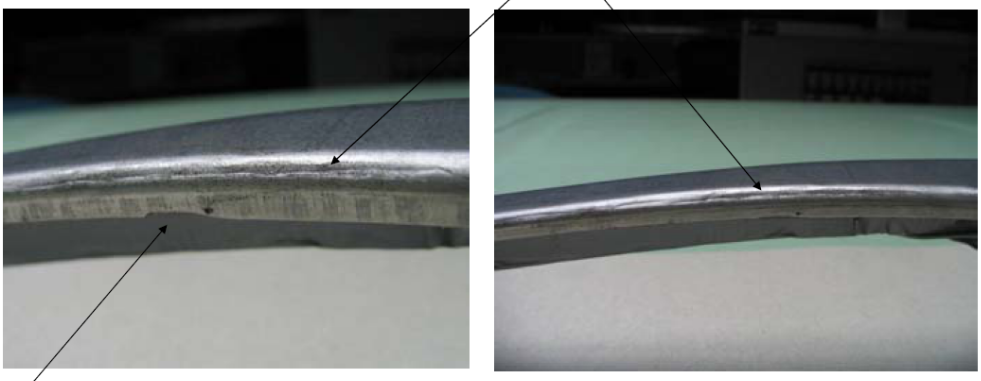
SPRINGBACK CONTROL HISTORY

- Initial compensation cut into die was approximately 80% of predicted spring-back.
- Spring-back compensation for the crown of the part had a significant effect on the flange spring-back.
- Die was cut 5 times due to the effect of the crown compensation on the flange.
- Added formations on the flange provided a much more consistent form.
- Spring-back was slightly reduced after formations were added to the flange.

RADII & EDGE FRACTURE CONDITIONS

- Radii fracture due to ISM bend radius error (1mm die radius instead of 2.5 "T" or 3.75mm rad.)



- Similar part experienced edge fracture in the match-cut condition of the trim. (Experienced in production due to tool wear)

PRESS LOAD PREDICTION ACCURACY

Die Stage	Press Loads (Metric Tons)				
	Estimate	CAE Prediction	Actual Meas.	Total Available	%
Progressive Die All stations combined	1780 M/T	Forming only 40 M/T	1300M/T	2000	65%
Trimming	1068				
Forming	712				

Due to all of the work being done under one ram, actual tonnage for each operation is not measurable. The majority of the press tonnage required to make these parts comes from trimming and piercing.

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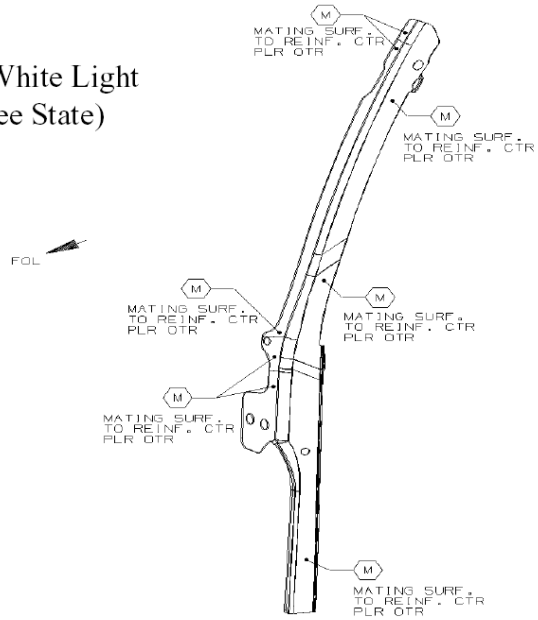
FIXTURING AND CLAMPING

- Holding fixture for White Light scanning of part. (Free State)



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POST-LAUNCH EXPERIENCE

Describe any insights gained during production

- Tool maintenance intervals – Trim steel sharpening after 40,000 hits
- Heat buildup issues – Parts are hot at end of line, but no dimensional issues
- Tool wear rate -
  - Re-coating flange steels after 40,000 hits is required.
  - Lower trim steels show grooves along die life surface.
- Tool breakage problems – NA – after 100,000 hits
- Part stability/spring-back problems – Die compensation corrected spring-back. No concerns in production
- Steel property variability effects – No effect from coil to coil
- Tonnage required. 1400 Metric Tons
- No issues with die running 40 SPM
- EOL issues – Parts are hot but manageable

LESSONS LEARNED

Overall Insights Gained – Product Design

- DP980 material does not compress well, take-up formations should be added when compression exceeds 3%
- Inside bend radius should be 3 x "T" minimum, particularly when plan view and elevation changes exist
- Provide for 15 degrees open wall angle on flanges to allow for compensation in the die.
- Minimizing crown in the top of the part will reduce spring-back

LESSONS LEARNED

Overall Insights Gained – Trimming / Forming

- Add shear on trim punches to reduce tonnage in trim stations.
- Trimming after form increases tool wear significantly resulting in burrs. (Develop trim when possible)
- Avoid placing trim by-pass in stretch / compression areas of part. Edge fracture may result if not followed.
- Robust die sections with heels, and keys for thrust must be used.
- Flange steels must be coated. (vanadium carbide recommended)
- Design for small replaceable sections in high were areas.
- Plan for several re-cuts when designing form stations. IE: Pad thickness, Post thickness, inserts
- Any compensation used on one area of the part, effects adjacent areas of the part.

Case Study Summary #8

Part Name	Reinf.- Mid-Rail Upper - R&L	**Material/Grade :**	DP 420/780	**Thickness:**	1.2 mm.
Coating :	HD 60G60GU	**URL for Full Case Study**:	www.a-sp.org/publications.htm		

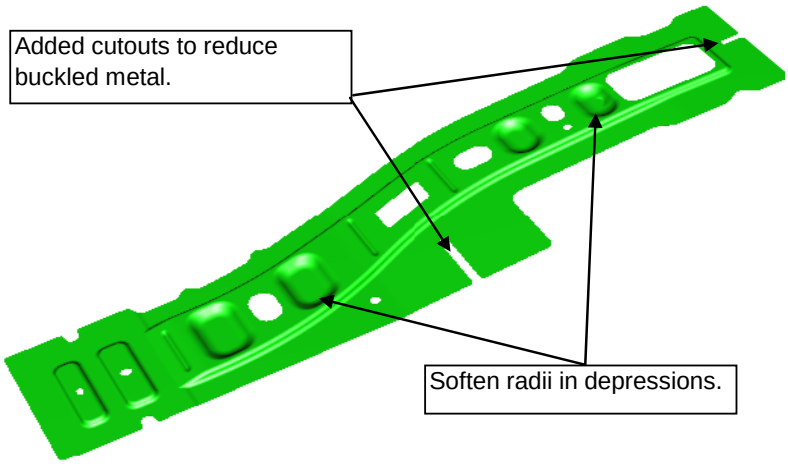
Spring-back/Twist Countermeasures: Re-cut die for longitudinal twist compensation.

Manufacturing Process

No. of Dies- 1	Prog. Die	(11) stations	40 spm				

Diagrams / Illustrations

Part Geometry

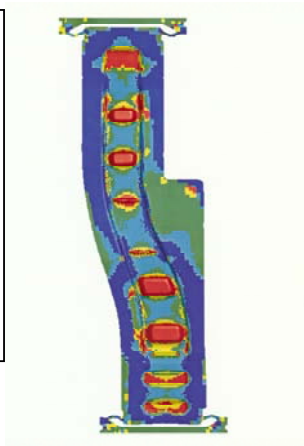


Deformation Map

Blue-
Uniaxial compression

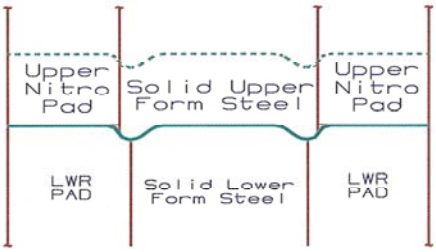
Red-
Biaxial stretch forming

Others-
Uniaxial tension



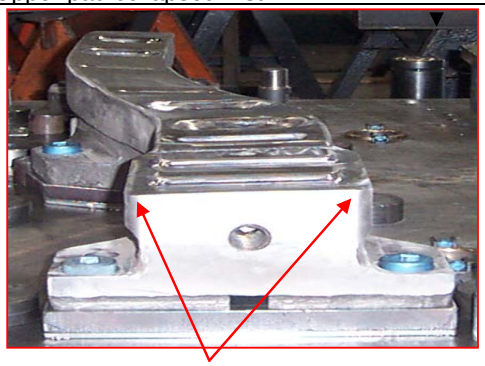
Die construction considerations

Upper Pad - 18 tons
Pad Travel - 41mm.



Lower Pad - 118 tons
Pad Travel - 15 mm.

Note: Sidewalls are formed before center depressions.
Upper pad collapsed first.



Compensation for stamping twist on die punch.

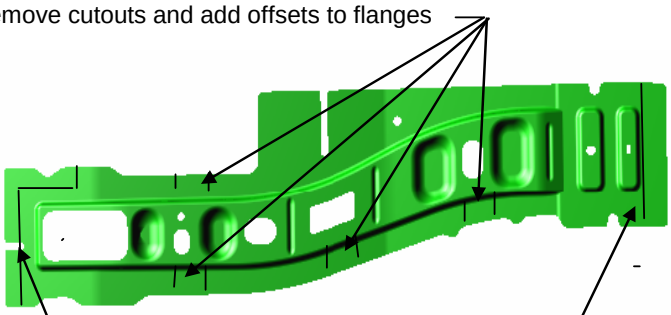
Notes

- Die had several re-cuts to compensate for twist in finished part.
- 40 SPM production rate required in-die stacking accumulator.
- No heat buildup issues.
- Stamping changes shape after trimming.
- Excessive wear and chipped edges on trim steels.

Die Construction and Tryout Information

Forming of sidewalls before center depressions may not be the optimum forming mode for this type of part. Stamper now feels that center depressions should be formed before sidewalls.

Recommendations for future designs -
Remove cutouts and add offsets to flanges



Add metal thickness offsets on surface

Upgrade die materials for all trim steels.

CASE STUDY #8: REINF0RCEMENT – MID-RAIL UPPER

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Advanced Vehicle Die & Stamping Engineer
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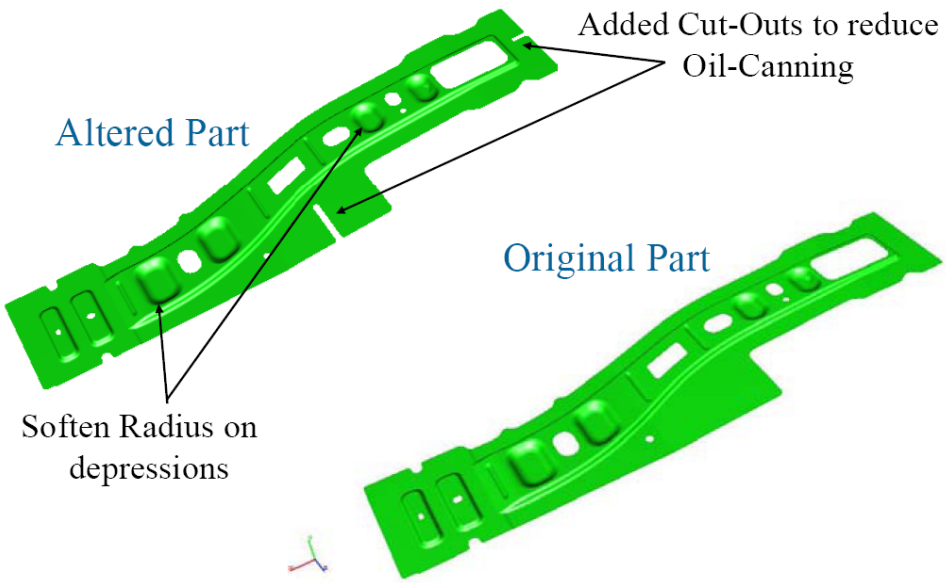
PART DESCRIPTION

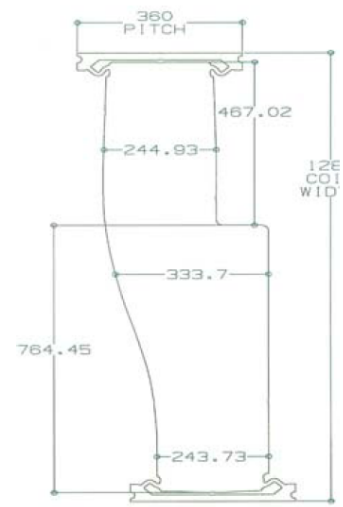
Part Name: Reinf. – Mid-Rail Upper - R & L



MATERIAL DESCRIPTION

Specification

Steel Grade	DP 780 (420Y/780T)
Coating	HD60G60GU
Gauge	1.2 mm
Coil Width	1284 mm
Coil Pitch	360 mm
Blank Shape	Developed
Lubrication	Mill Oil



Progressive Die Blank Development

PRESS LINE

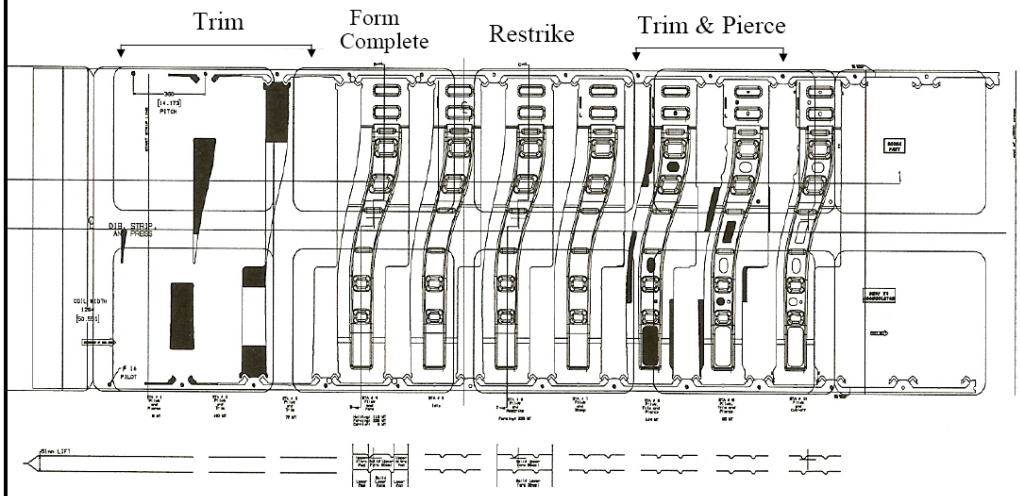
Press Information

Progressive Die Press :	5500 mm High Speed Progressive Die Press.
Slide Tonnage	2000 Tons
SPM	40 SPM
Current Production Rate:	40 SPM (In-Die stacking for part handling throughput)

STAMPING PROCESS

Process Overview: **Progressive Die – 11 Stations**

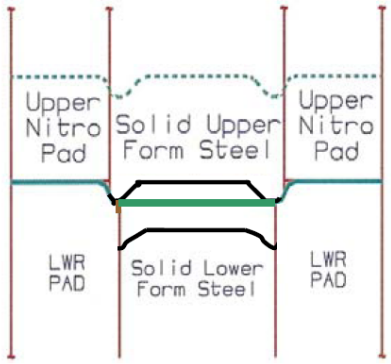
Separate Progressive Dies for Rt. and Lt. Hand Parts



Process Flow

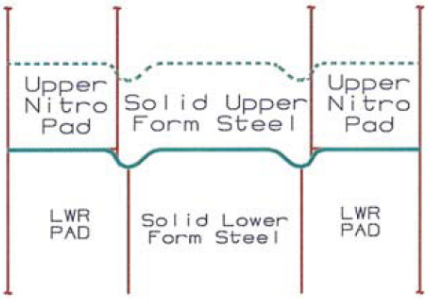
FIRST FORM

Form with Upper and Lower Pressure Pads and Solid Upper & Lower Forming Steels.



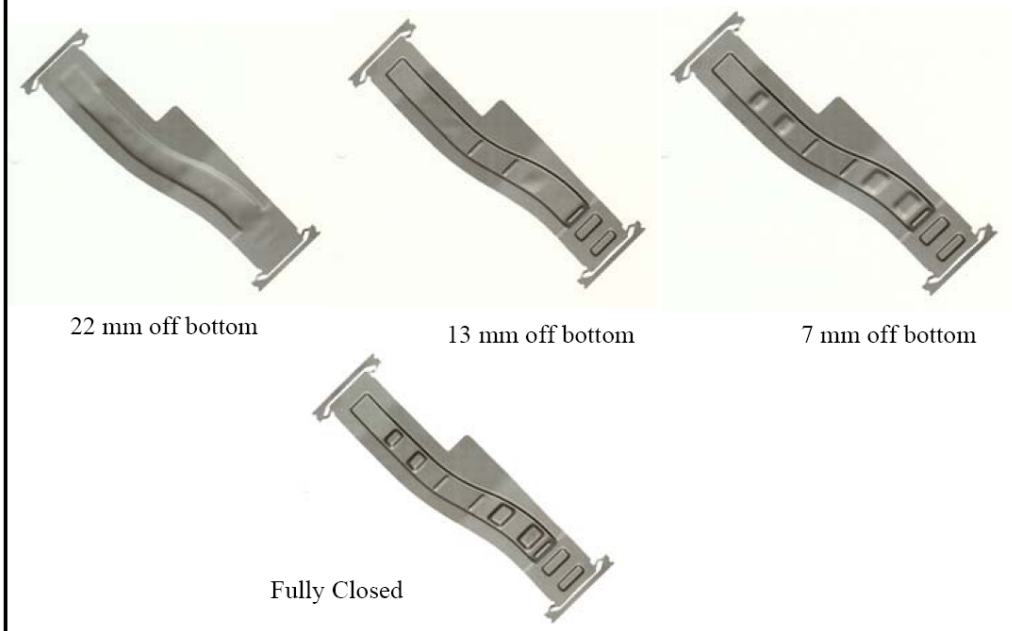
Upper pad collapsed, Lower pad still un-traveled

Upper Pad - 18 Tons
Pad Travel – 41 mm



Lower Pad - 118 Tons
Pad Travel – 15 mm

SIMULATION BREAKDOWN

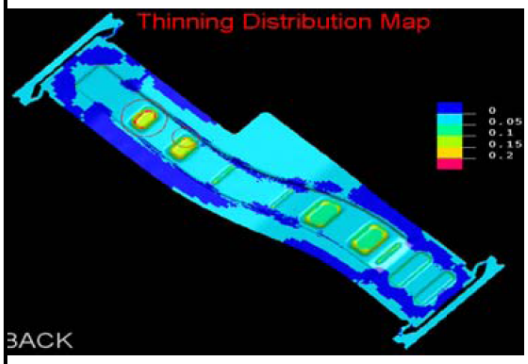


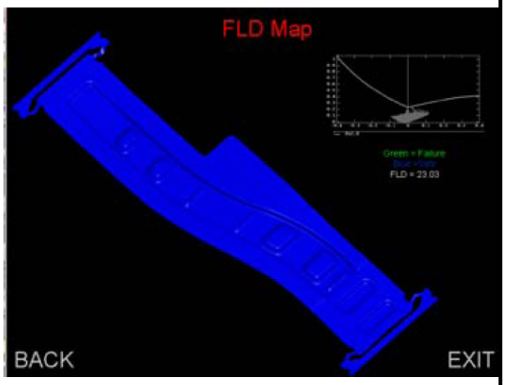
THINNING DISTRIBUTION / FLD MAP

Pam Stamp and Autoform showed similar results

Maximum thinning predicted to be 20%

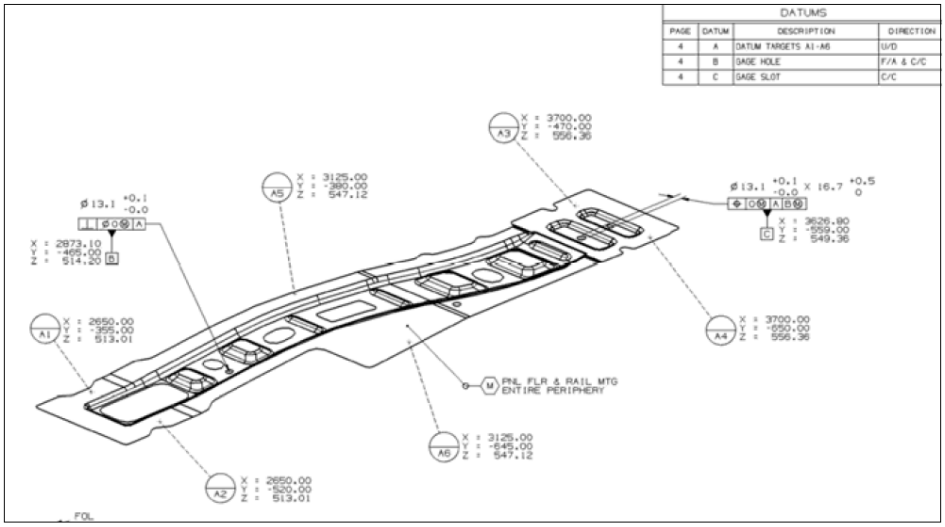
Passing FLD supported the forming process



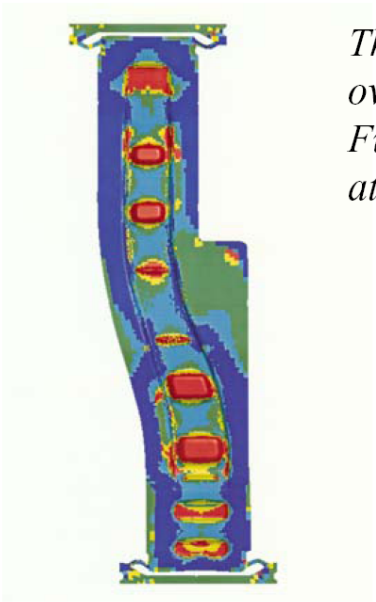


GD&T DRAWING

Datum structure used the least stable surfaces of the part as the "A" datum



DEFORMATION MAP



This Information may have been overlooked as non-value added. Future projects should pay close attention to this data.

Deformation Mode Map

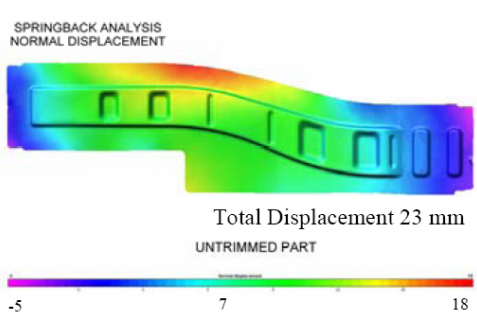
Blue – uniaxial compression

Red – biaxial stretch forming

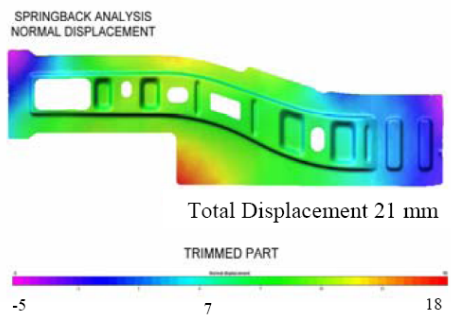
Others - uniaxial tension

FEA SPRINGBACK ANALYSIS

- **Untrimmed vs. Trimmed Part Spring-back**



Untrimmed Part



Trimmed Part

RADII FRACTURE / SPRINGBACK

Splits – Experienced splits when thinning exceeded 11%

Spring-Back & Twist - Up to 12 mm out of spec.

NEGOTIATED PRODUCT GEOMETRY

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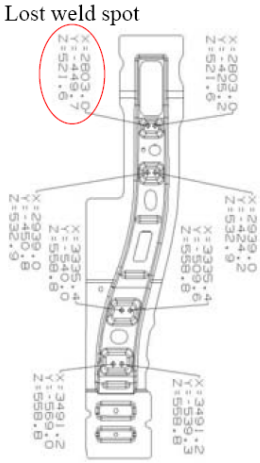
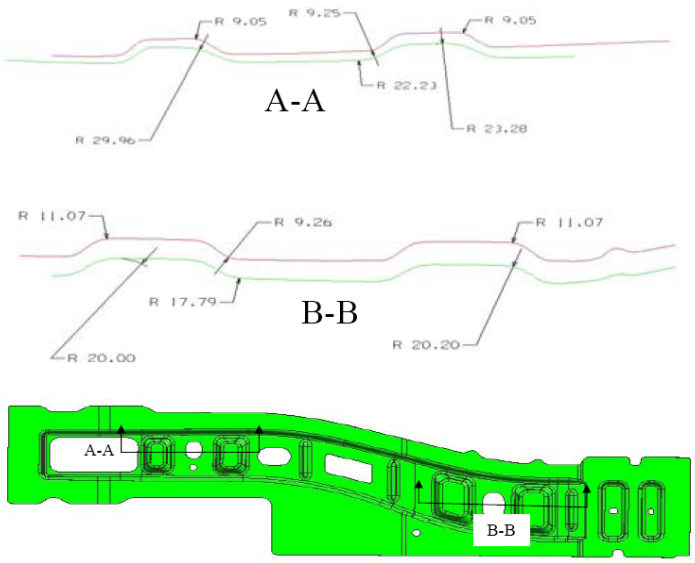
FORCED PRODUCT CHANGES

= Original

= Current

Lost weld spot





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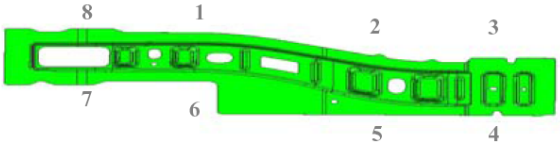
SPRING-BACK COMPENSATION

Morph Values to Product

	PT 1	PT 2	PT 3	PT 4	PT 5	PT 6	PT 7	PT 8
Morph 1	-16	-5.2	+5.2	+3.2	-6	-7.6	+1.8	+2
Morph 2	-15.0	-7.2	+14.5	+14.4	-7.4	-4.3	+4.7	-7
Morph 3	-7.4	-4.1	+2.6	-5	-16.1	-7	-15.7	+15.2
Morph 4	-22	-17.5	-2.3	-5.94	-24	-8.4	-1.9	-5.1
Morph 5	-26.8	-16.8	-.25	-7.7	-26.5	-9.9	+.4	-6.5

Measurement Data to Product

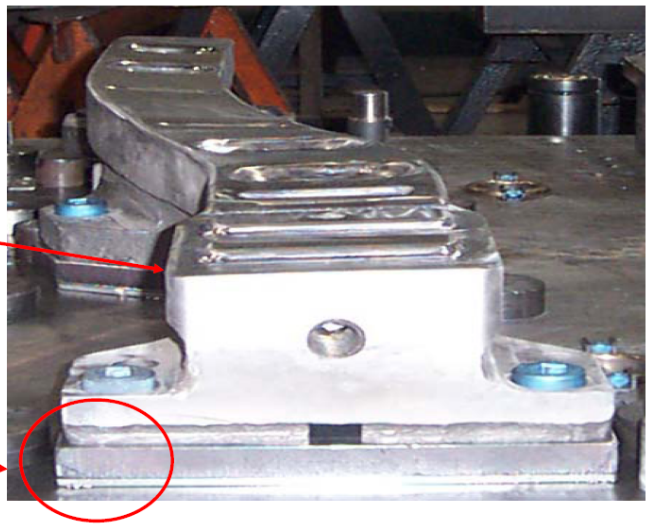
	PT 1	PT 2	PT 3	PT 4	PT 5	PT 6	PT 7	PT 8
Result 1	-2.8	-.3	-3	-3	+.75	-3	-.5	0
Result 2	-1	-3	-2	-2	-2	-3	-1.75	-1.75
Result 3	-.5	-3	-1.5	-2	-2	-2	-3	+.2
Result 4	-2	-.75	-.75	+1.1	+.1	-2	-2.8	-3
Result 5								



RE-CUTS TO POST

Compensation for twist on upper draw post

Several Re-Cuts caused excessive shims



PRESS LOAD PREDICTION ACCURACY

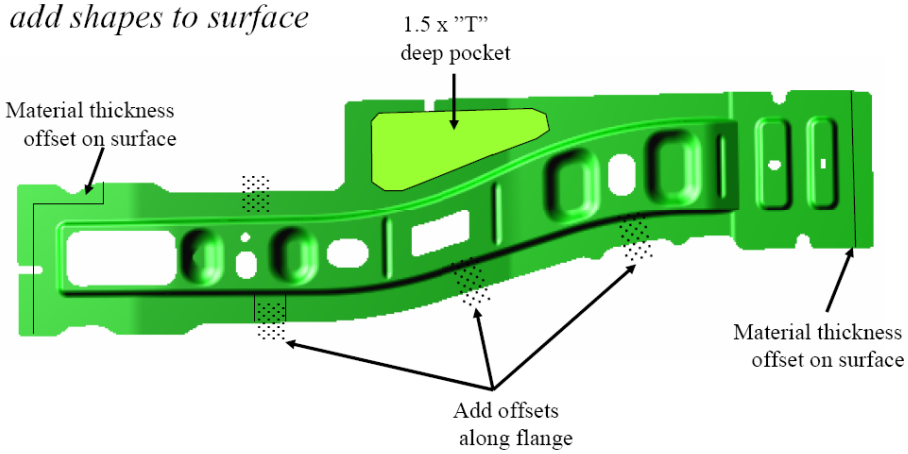
Die Stage	Press Loads (Metric Tons)				
	Estimate	CAE Prediction	Actual Meas.	Total Available	%
Progressive Die All stations combined	1048	NA	1000	2000	50
Trimming	245	NA	NA		
Forming	361	NA	NA		

Due to all of the work being done under one ram, actual tonnage for each operation is not measurable. The majority of the press tonnage required to make these parts comes from trimming and piercing.

LESSONS LEARNED

Recommendations for future design

Remove cut-outs and add shapes to surface



POST-LAUNCH EXPERIENCE

Insights gained during production

- **Heat buildup issues -** No heat buildup issues
- **Tool wear rate -** Trim Steel wear continues to be a problem
- **Tool breakage problems** – Chipped edges on trim steels
- **Dimensional stability and robustness** – Unstable, GD&T was opened up to accept production variation.
- **Steel property variability effects** – Fluctuation of part quality between coils of steel is a continuing problem

LESSONS LEARNED

SUMMARY

- Process should have been changed to form center depressions before side-wall breaks, or draw the part complete with conventional draw die
- FLD failure curve for DP800 material must be adjusted to a more conservative level
- Product geometry must include formations to help hold shape of the part
- Trimming the panel changes the location and amount of spring-back on the part
- There must be ongoing studies to find a solution for tool wear when stamping AHSS

Case Study Summary #9

Part Name	Reinf.- A-Pillar Upr.- R & L	**Material/Grade :** (see illustration)	**Thickness:** 2.0 mm
Coating :	HD Galvanneal 40A40A	**URL for Full Case Study:**	www.a-sp.org/publications.htm

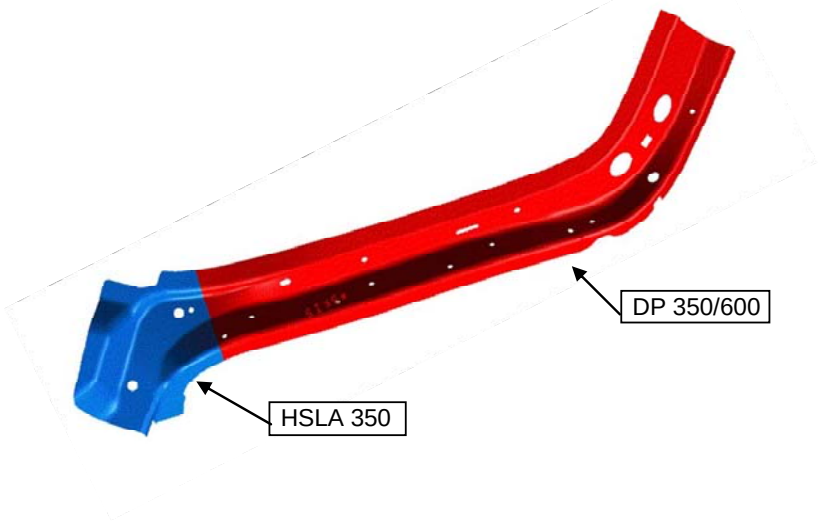
Spring-back/Twist Countermeasures: Increased draw binder pressure and tonnage in restrike die.

Manufacturing Process

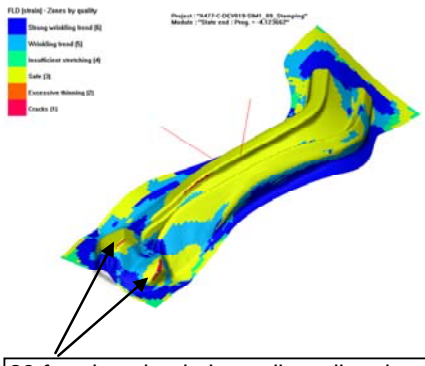
No. of Dies- 5	Draw	Tr., Prc., Cam Prc.	Cam Trim & Prc.	Restrike	Cam Prc.		

Diagrams / Illustrations

Part Geometry



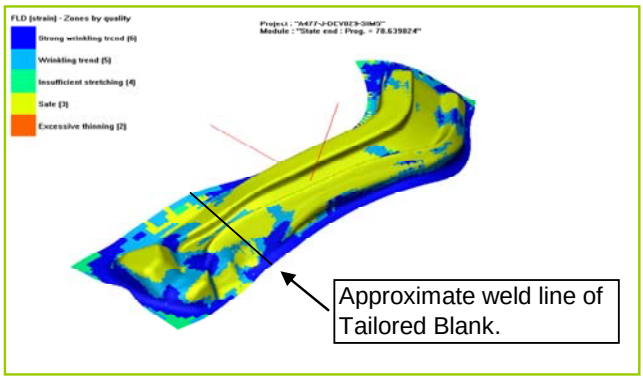
Forming Simulation



29 forming simulations all predicted splitting of DP 600 material. A tailor-welded blank became the solution to meet formability requirements.

Die construction considerations

A tailor welded blank (HSLA 350/DP 600 MPa) is used to meet formability requirements.

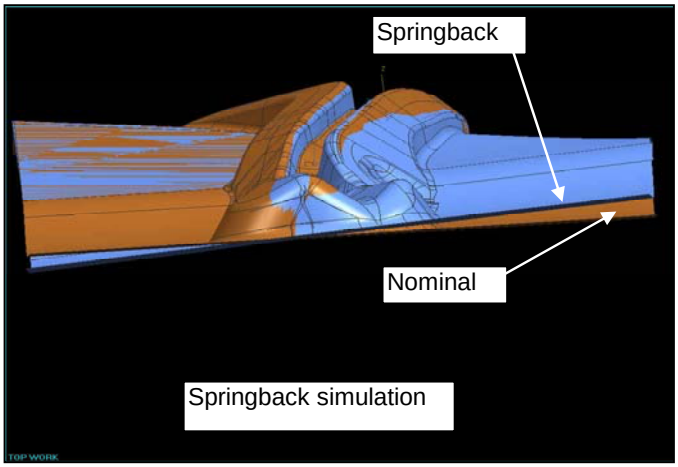


Trimmed stamping sprung 15mm off punch in initial tryout.

Notes

- Draw die required 2 re-cuts for springback compensation.
- Chipped trim steels require excessive maintenance.
- Upgrade die materials in future for trim steels & scrap cutters.
- PM intervals - 50,000 hits. Trim dies - after every run.
- Minor dimensional variation run to run. Stable within run.

Springback Information



Die adjustments during production to solve problems:

- Draw die gage and nitro pressure adjustments.
- Amount of draw compound.
- Adjust tonnage in restrike die.

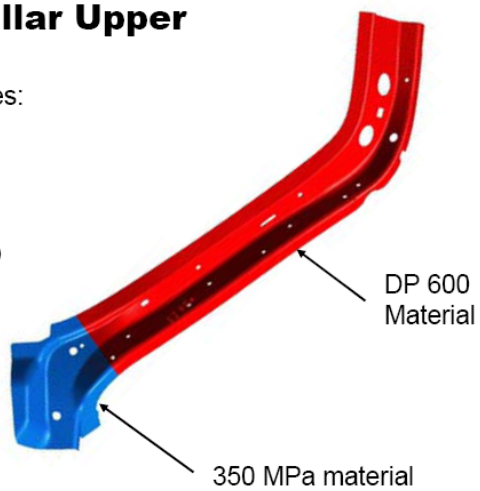
CASE STUDY #9:
REINF. – A-PILLAR UPPER

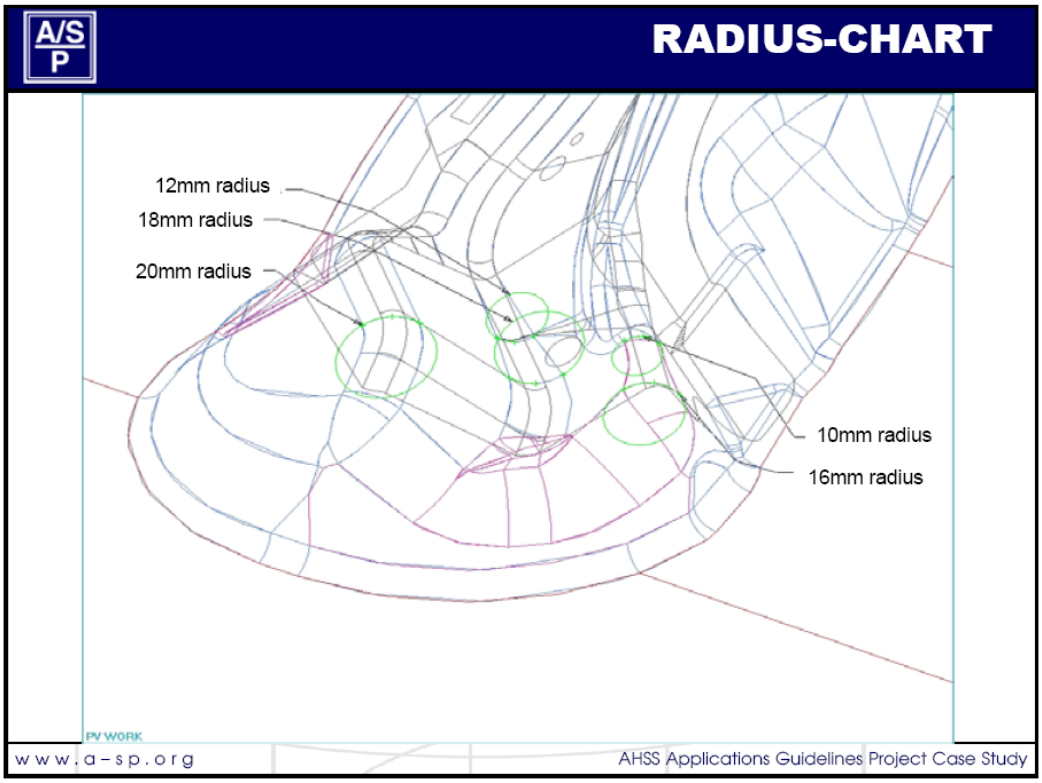
Kerry Fitzgerald
AZ Automotive Corp.
AZautomotive.com
kfitzgerald@azautomotive.com

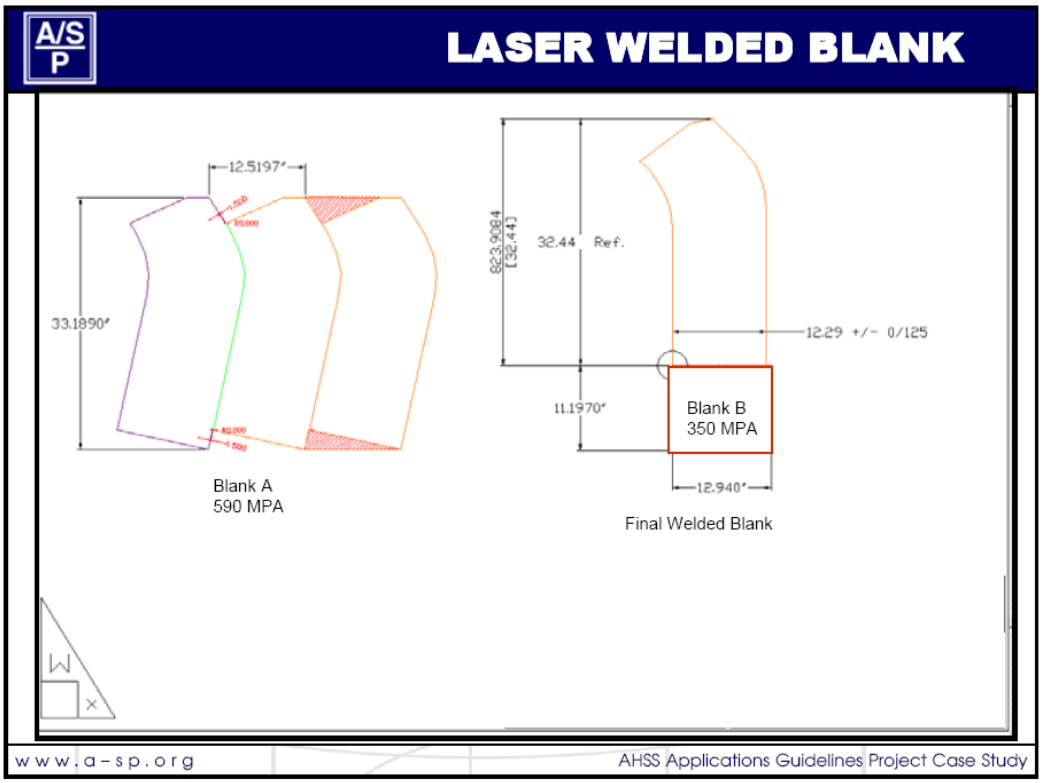
PART DESCRIPTION

Part Name: Reinf-A-Pillar Upper

- Mating surfaces and critical features:
  - -Flanges all around.
  - -Free state shape
  - -Laser welded blank
- Critical radii: – Lower End (carryover)
- Depth of draw: – 120mm
- Lower End 350MPa Material




RADIUS-CHART
12mm radius
18mm radius
20mm radius
10mm radius
16mm radius
PV WORK
www.a-sp.org
AHSS Applications Guidelines Project Case Study


LASER WELDED BLANK
12.5197"
33.1890"
Blank A
590 MPA
823.9084
[32.44]
32.44 Ref.
12.29 +/- 0/125
11.1970"
Blank B
350 MPA
12.940"
Final Welded Blank
www.a-sp.org
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MATERIAL DESCRIPTION

Laser Welded Blank

Blank A		Blank B	
Steel Grade:	DP 600	Steel Grade:	350 MPa HSS
Coating:	HDGA	Coating:	HDGA
Gauge:	2.0mm (.079 in)	Gauge:	2.0mm (.079 in)
Blank Width:	843mm (33.189 in)	Blank Width:	328mm (12.95 in)
Blank Pitch:	320mm (12.60 in)	Blank Pitch:	284mm (11.187 in)
Yield:	390 MPa	Yield:	345 MPa
Tensile:	590 MPa	Tensile:	414 MPa
n-value:	0.169	n-value:	0.158
r-value:	0.89	r-value:	1.0
K-value:	990 MPa	K-value:	807 MPa

Simulation Values

Yield:	370 MPa	Yield:	376 MPa
Tensile:	602 MPa	Tensile:	480 MPa
n-value:	0.16	n-value:	0.156
r-value:	0.9	r-value:	0.86
K-value:	947 MPa	K-value:	718 MPa

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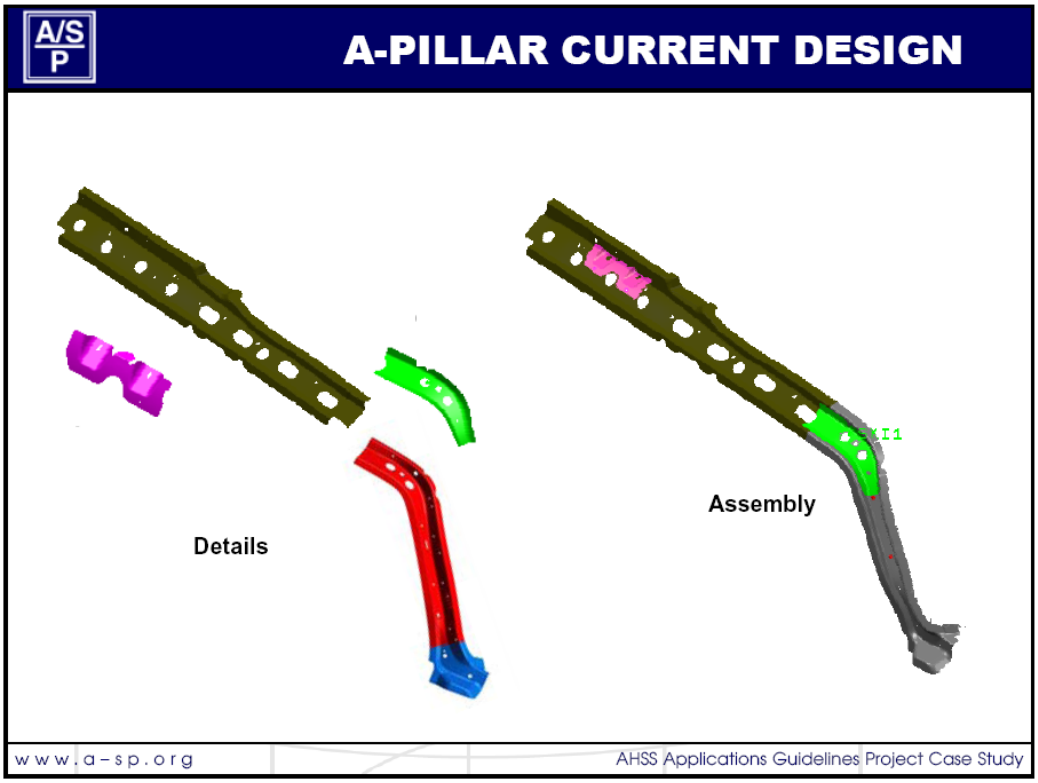
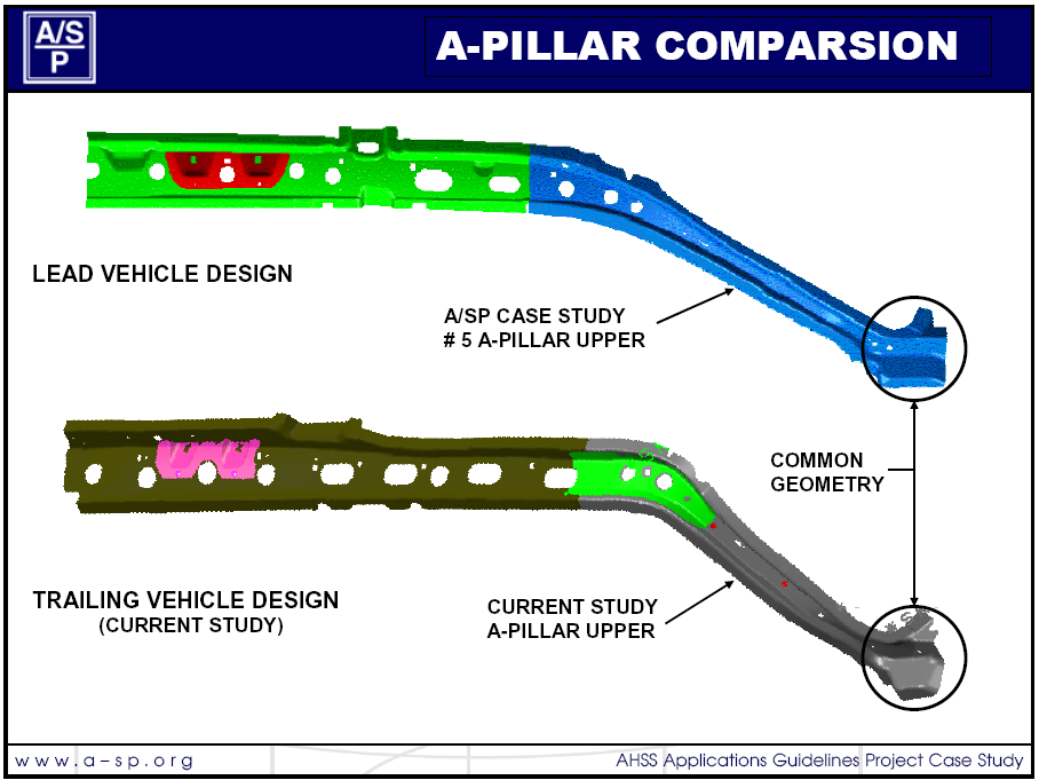
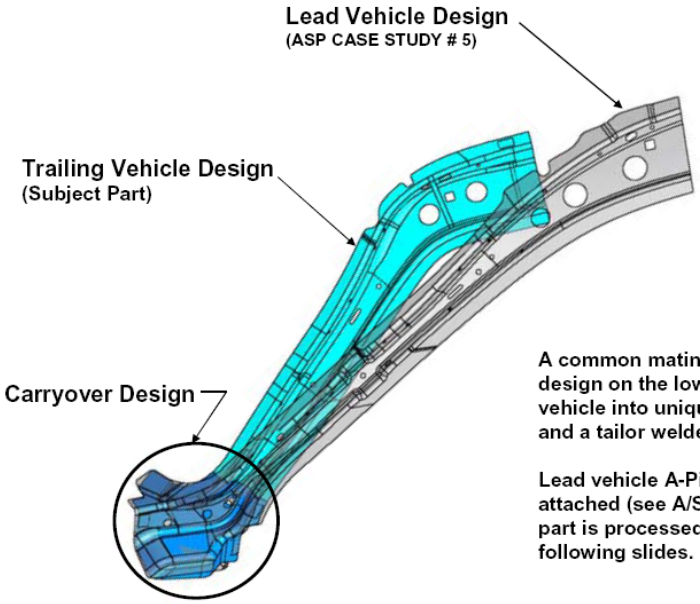
PART HISTORY

www.a-sp.org AHSS Applications Guidelines Project Case Study


A/S P
A-PILLAR CURRENT DESIGN
Details
Assembly
www.a-sp.org
AHSS Applications Guidelines Project Case Study


A/S P
A-PILLAR COMPARSION
LEAD VEHICLE DESIGN
A/SP CASE STUDY
5 A-PILLAR UPPER
COMMON
GEOMETRY
TRAILING VEHICLE DESIGN
(CURRENT STUDY)
CURRENT STUDY
A-PILLAR UPPER
www.a-sp.org
AHSS Applications Guidelines Project Case Study

GEOMETRY COMPARISON



A common mating surface required carryover design on the lower end. This forced the trailing vehicle into unique part geometry, die processing and a tailor welded blank.

Lead vehicle A-Pillar was processed double attached (see A/SP Case Study #5). The subject part is processed single as shown in the following slides.

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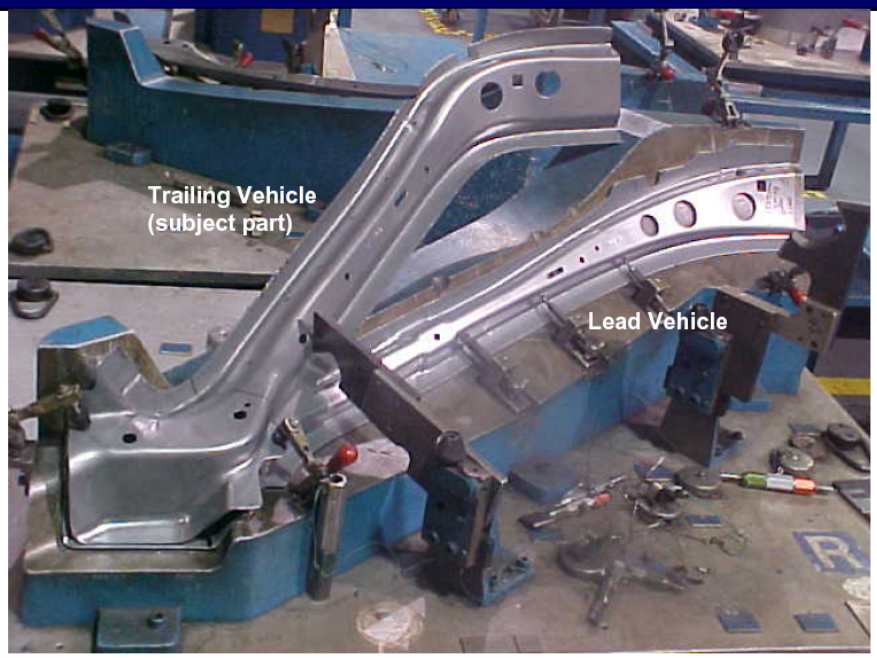
ACTUAL PART COMPARISON



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DIE PROCESSING

PRESS LINE CONSTRAINTS

Press line assigned to this part.

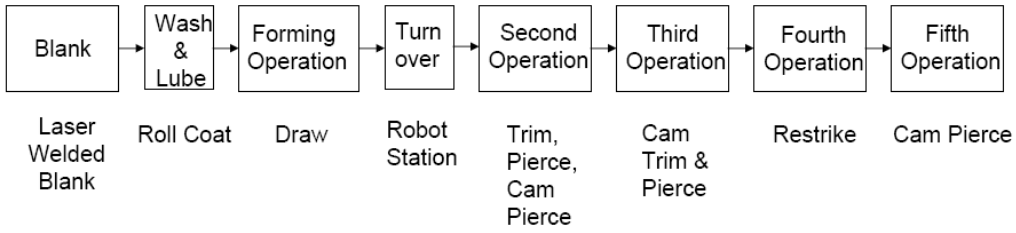
Press #1: Type	Muller (Hyd)	Bed size	158 x 94	Press tonnage	2000
Press #2: Type	Verson (Mech)	Bed size	102 x 72	Press tonnage	1000
Press #3: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #4: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000
Press #5: Type	Verson (Mech)	Bed size	120 x 72	Press tonnage	1000

Target production rate - 375 / hr

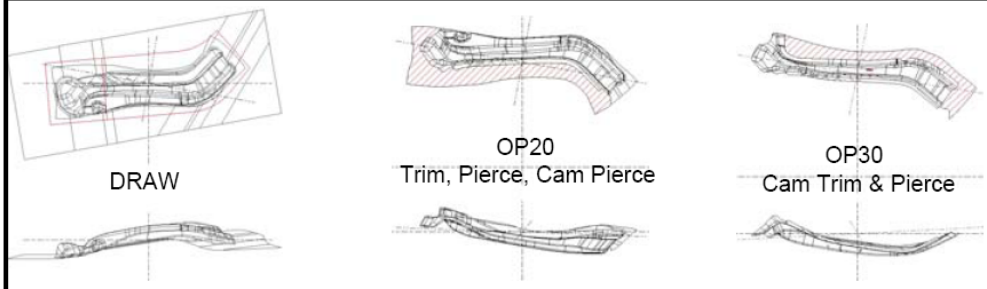
Die-applied cushion pressure.

STAMPING PROCESS DESIGN

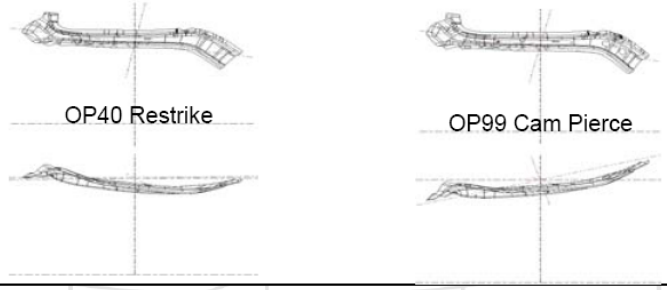
Process Flowchart: Single



STAMPING PROCESS DESIGN

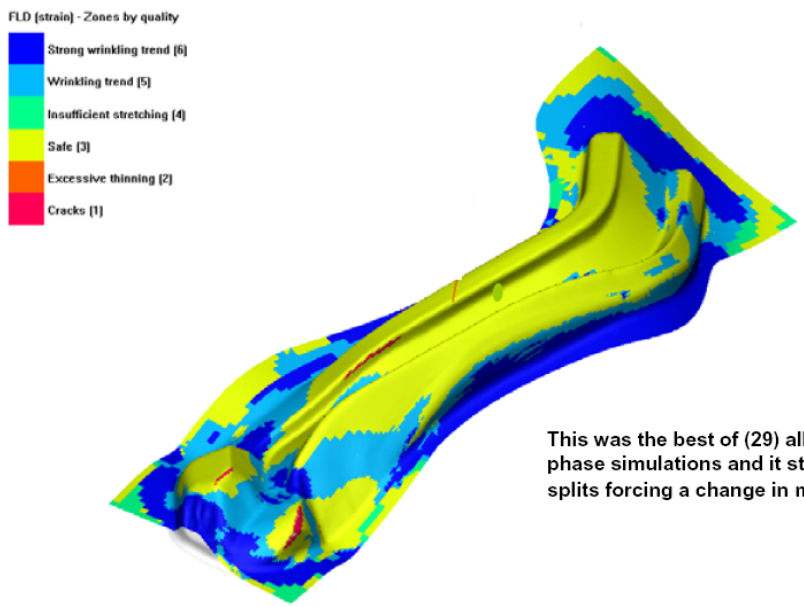


DIE LOCK IN THE DRAW AND TRIM ANGLES IN THE TRIM OPERATIONS REQUIRED PART TIPS THAT WOULD NOT ACCOMMODATE A DOUBLE ATTACHED PROCESS. THE PART IS TURNED OVER BETWEEN OP10 AND OP20 SO HOLES ALONG THE CENTER SECTION CAN BE CAM PIERCED.



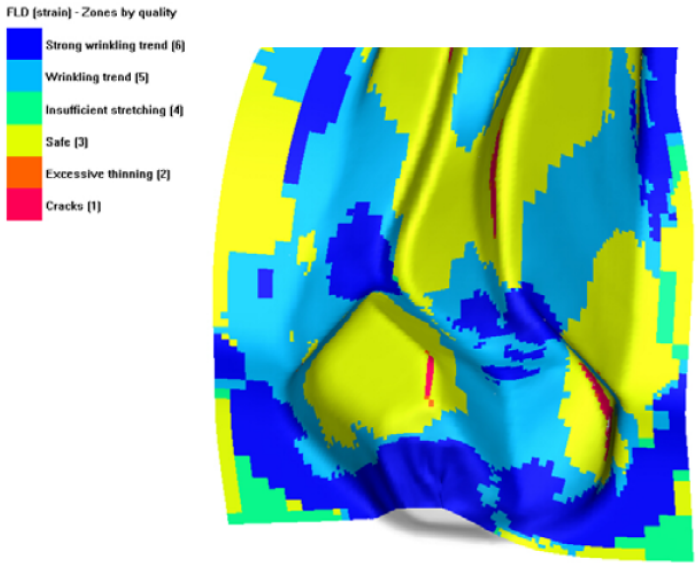
FEA FORMABILITY ANALYSIS

ALL DUAL PHASE

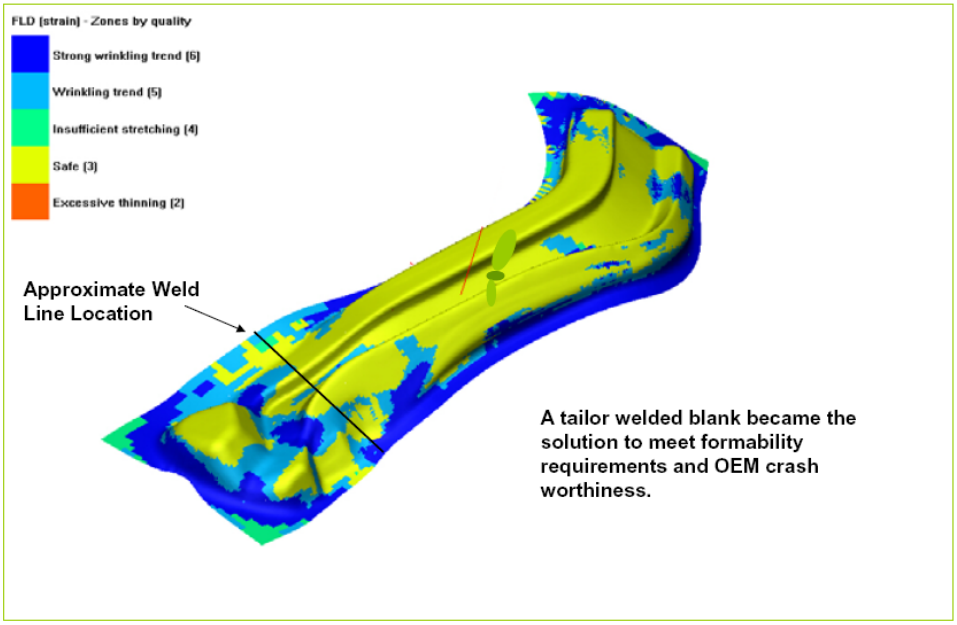


This was the best of (29) all dual phase simulations and it still showed splits forcing a change in material.

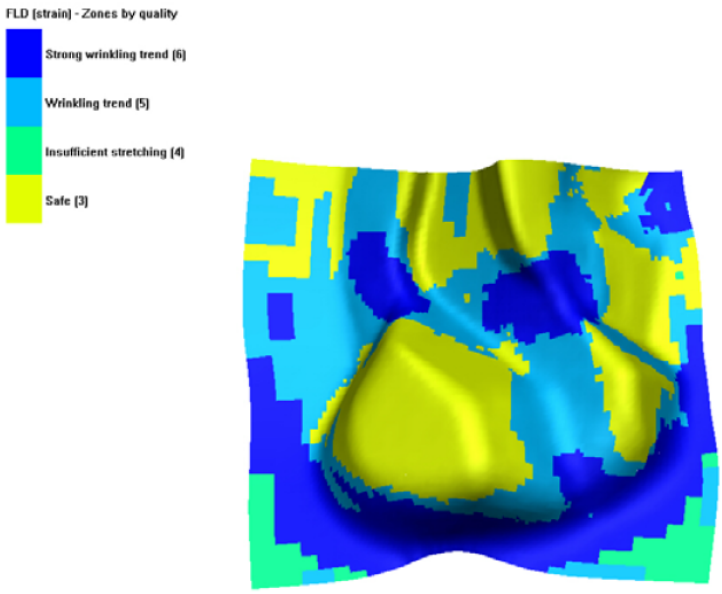
DUAL PHASE FRONT



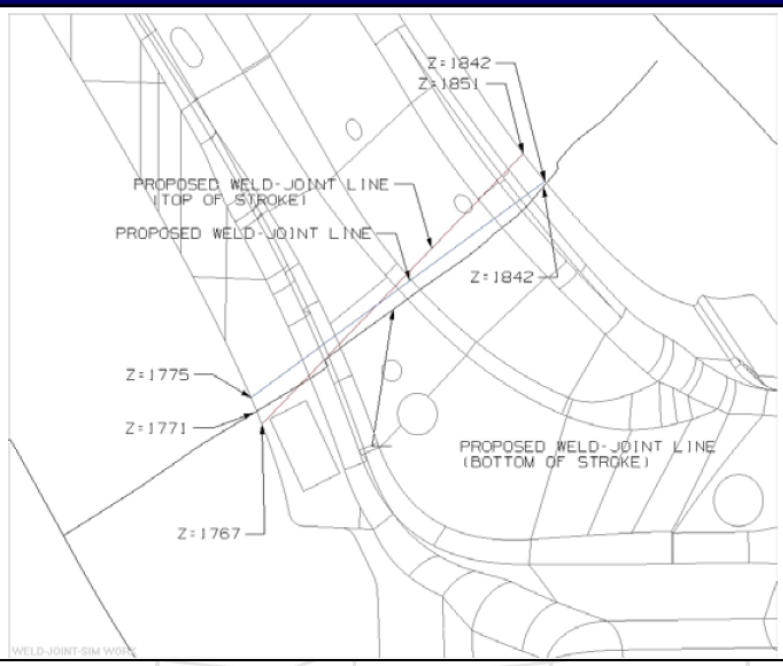
FINAL WELDED BLANK



FINAL FRONT END - 350MPa STEEL



WELDLINE PROPOSAL

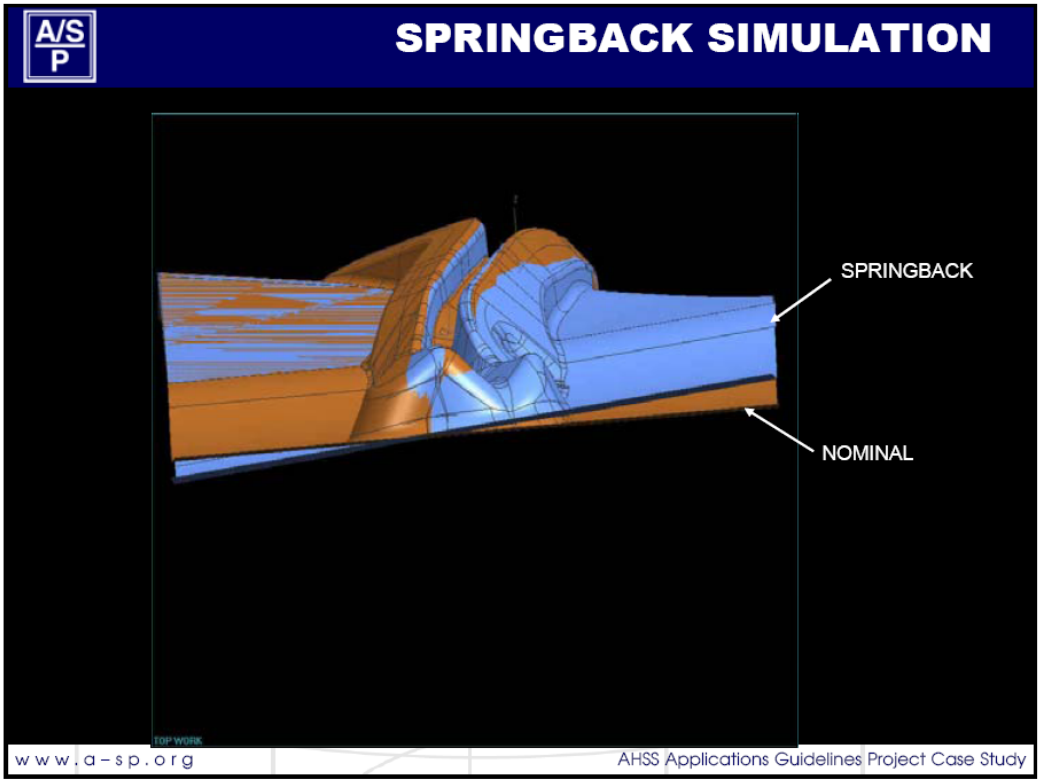


DIE CONSTRUCTION & TRYOUT

SPRINGBACK COMPENSATION

Approach to controlling springback

- Cut to nominal and re-cut to control
  - Morph springback into model 1 to 1 ratio
  - Re-cut to morphed geometry
  - (2) re-cuts


SPRINGBACK SIMULATION
SPRINGBACK
NOMINAL
www.a-sp.org
AHSS Applications Guidelines Project Case Study


ACTUAL SPRINGBACK (Part on Punch First Cut)
www.a-sp.org
AHSS Applications Guidelines Project Case Study

SPRINGBACK MEASUREMENT

PRODUCTION

FINAL SPRINGBACK CONTROL MEASURES

Springback controls employed successfully during production:

- Adjusting binder pressure in draw
- Adjusting tonnage in restrike

PRODUCTION PART ON FIXTURE (Free State)

MEASUREMENT (tolerance + / - .75)

PRESS LOAD PREDICTION ACCURACY

Die Stage	Press Loads (Tons)				
	Estimate	CAE Prediction	Actual Measured	Total Available	%
Forming Press Binder	1000	750 100	800 66	2000	40
Trim, Pierce	400	N/A	300	1000	30
Cam Trim, Pierce	400	N/A	300	1000	30
Restrike Press	900	N/A	800	1000	80
Cam Pierce, Separate	400	N/A	300	1000	30

POST-LAUNCH EXPERIENCE

Insights gained during production

- Tool maintenance intervals 50,000 hits
- Heat buildup issues solved by using drawing Compound
- Tool wear rates Form Dies: Polish 50,000 hits, Weld critical radii 150,000 hits
- Tool breakage problems: Chipped edges – should PM after each run
- Avoid knife edge trim angles (see following slide)
- Springback problems: Minor dimensional variation run to run, stable within the run.
- Steel property variability effects: Cause of run to run variation
- Die tweaks during production to solve problems:
    1. Draw die gage and nitro adjustment.
    2. Amount of draw compound.
    3. Adjust tonnage and pad pressure in restrike die.

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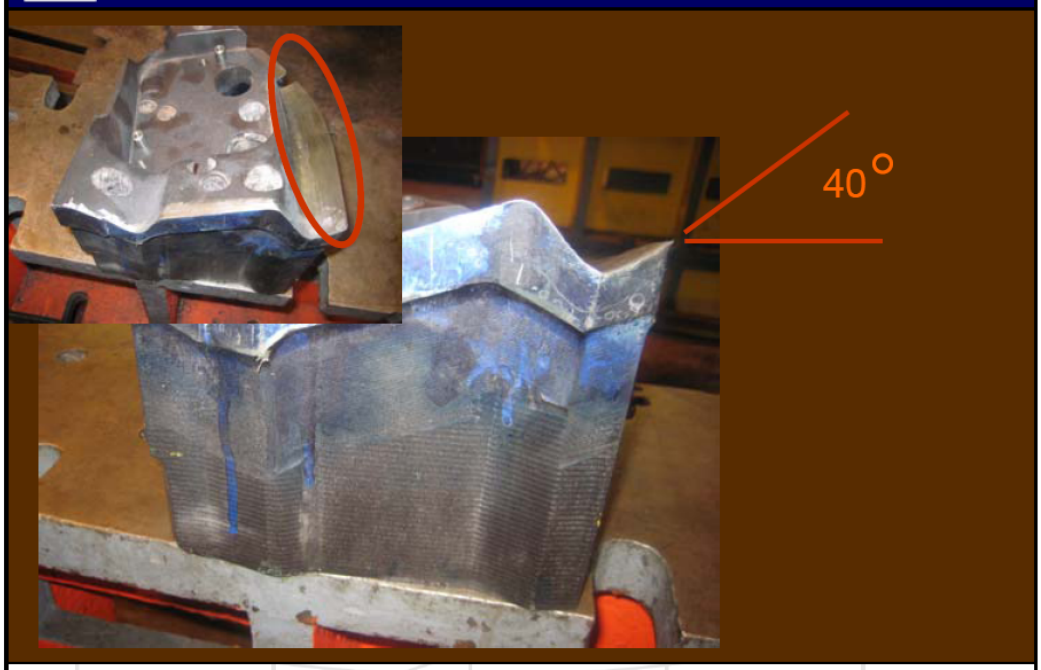
KNIFE EDGE TRIM CONDITION



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Case Study Summary #10

Part Name	Member - Floor Side Inner	**Material/Grade :**	DP 350/600	**Thickness:**	1.8 mm
Coating :	HD 60G60G	**URL for Full Case Study:**	www.a-sp.org/publications.htm		

Spring-back/Twist Countermeasures: Cut Draw Die to nominal, Re-cut to results of springback study.

Manufacturing Process

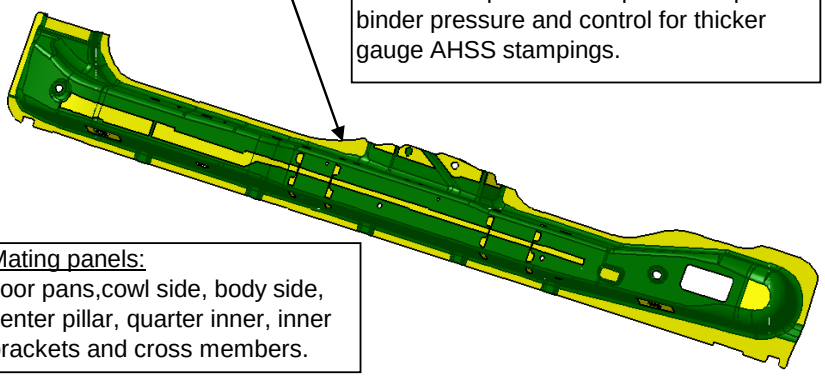
No. of Dies- 4	Draw Die	Tr. & Prc. Die	Tr. Prc& Cam Prc.	Form & Restrike Die			

Diagrams / Illustrations

Part Geometry

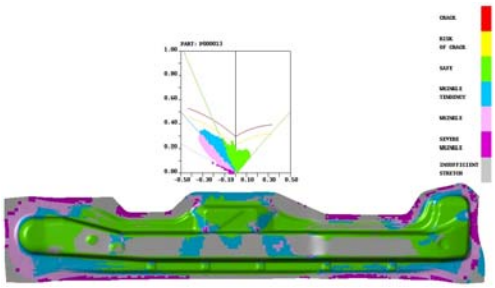
Mating surfaces shown in yellow.

This stamping was made with a double-action draw press which provides optimum binder pressure and control for thicker gauge AHSS stampings.



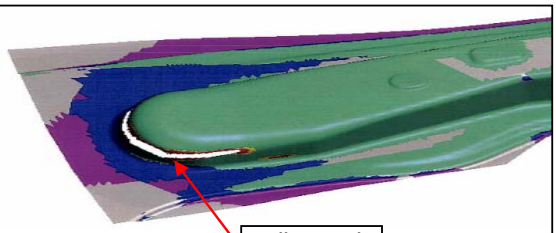
Mating panels:
floor pans,cowl side, body side, center pillar, quarter inner, inner brackets and cross members.

FLD



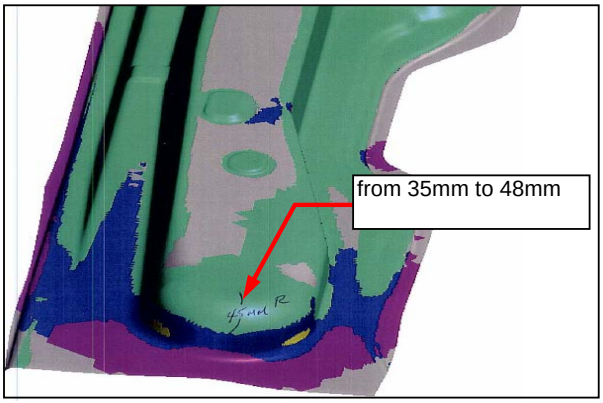
LS-Dyna Simulation - these results were used to proceed with die construction.

Die construction considerations



split metal

Split eliminated by shortening the blank and revising the radii and force of the step beads.

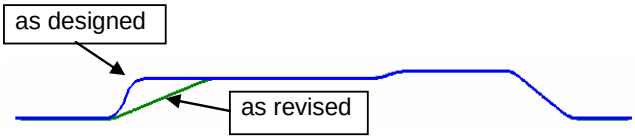


from 35mm to 48mm

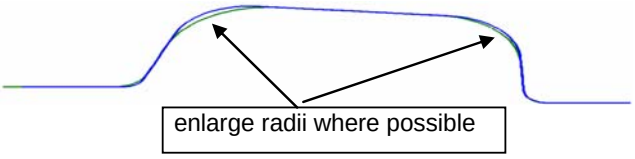
Notes

Due to springback, twist and sidewall curl an additional four cuts were required to bring the part to design intent.
Provide a more robust die constrruction for thicker gauge AHSS stampings to avoid cracked tooling.
Caldie™ inserts used on trim die lower post. (bar stock)
Carmo™ steel used for trim die upper sections. (cast steel)

Section Information



Revise steep sections to avoid splits.



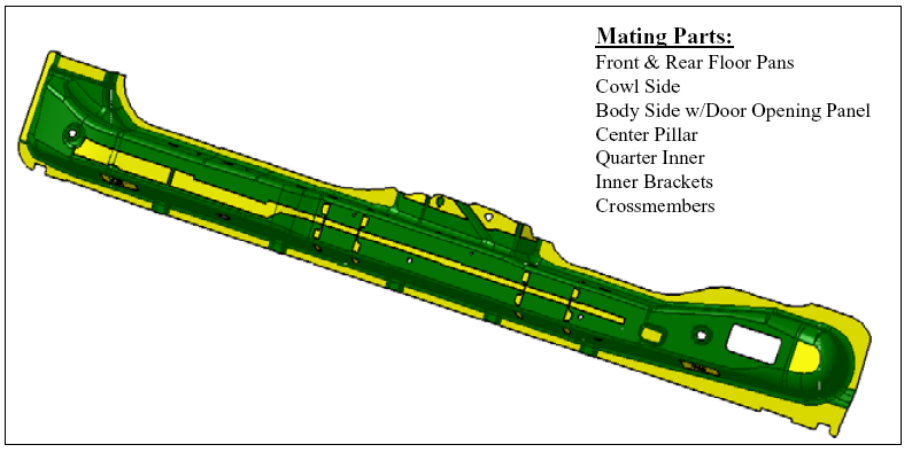
Larger radii reduce split problems and tool wear.

CASE STUDY #10:
MEMBER - FLOOR SIDE INNER

Eric Frevik
Process & Design Mgr.
efrevik@ford.com
Ford Motor Company
www.ford.com

PART DESCRIPTION

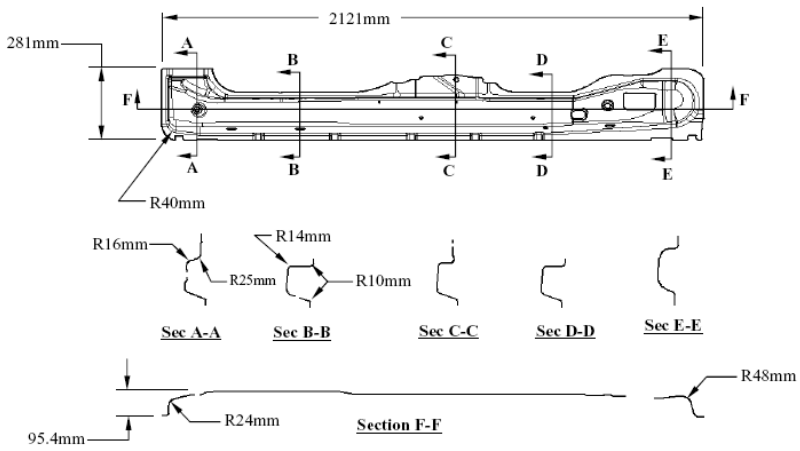
Part Name: **MEMBER-FLOOR SIDE INNER**
- Mating surfaces features highlighted in yellow.



PART DESCRIPTION

Part Name: **MEMBER-FLOOR SIDE INNER**

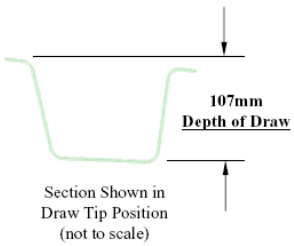
- Part Size: Length = 2121mm Height = 281mm Depth = 95.4mm
- Critical radii are shown in Plan View and Sections

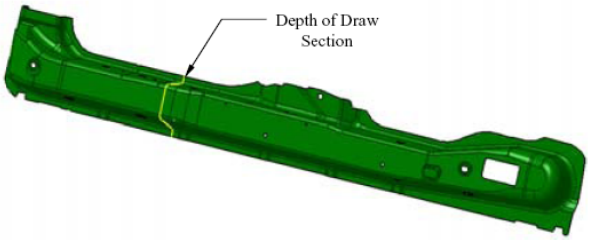


PART DESCRIPTION

- Part Name: **MEMBER -FLOOR SIDE INNER**

- Part features that limited formability:
  - Depth of Draw
  - Closed Ends
  - Dual Phase 600 Material
  - Critical Radii (shown on previous page)

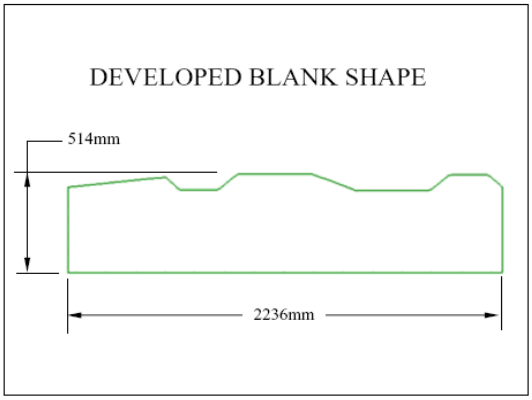




MATERIAL DESCRIPTION

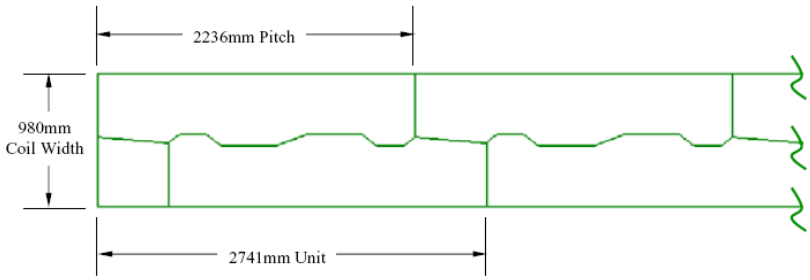
Steel Grade:	DP 600 (350Y/600T)
Coating:	HD 60G60G
Gauge:	1.80 mm
Blank Width:	514 mm
Blank Pitch:	2236 mm
Blank Shape:	(Developed)

Actual Material Properties:
(used for tryout & production)
Yield Strength: 362 MPa, 52.5 ksi
Tensile Strength: 636 Mpa, 92.2 ksi
Total Elongation: 24%
N: 0.166 (10% to U.E.)
R: 1.00
K: 963 MPa (10% to U.E.)



MATERIAL DESCRIPTION

BLANK NESTING



The same steel vendor was used for die tryout and production steel supply

PRESS LINE CONSTRAINTS

Part runs in a Tandem Press Line with Robot Load and Unload Automation

Press #1: Danly Dual Action, Bed size=144" X 96", Press tonnage=1800 US tons

Press #2: Clearing Single Action, Bed size=144" X 90", Press tonnage=1000 US tons, Nitro Upper Pad Pressure

Press #3: Same as Press #2

Press #4: Danly Single Action, Bed size=144" X 90", Press tonnage=1000 US tons, Nitro Upper Pad Pressure

Press #5: Same as Press #4

STAMPING PROCESS DESIGN

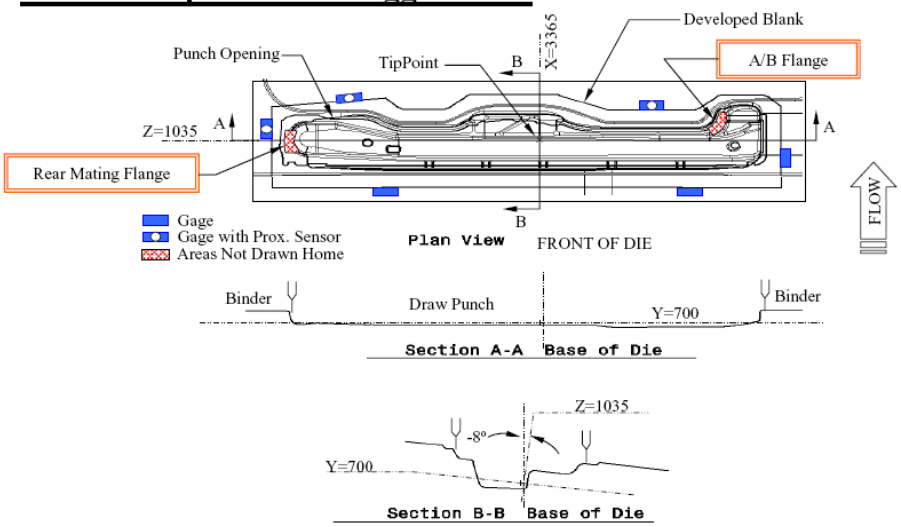
Process Overview

1st Operation: Dual Action Toggle Draw
2nd Operation: Idle (Turnover)
3rd Operation: Trim & Pierce
4th Operation: Trim, Pierce & Cam Pierce
5th Operation: Form & Restrike

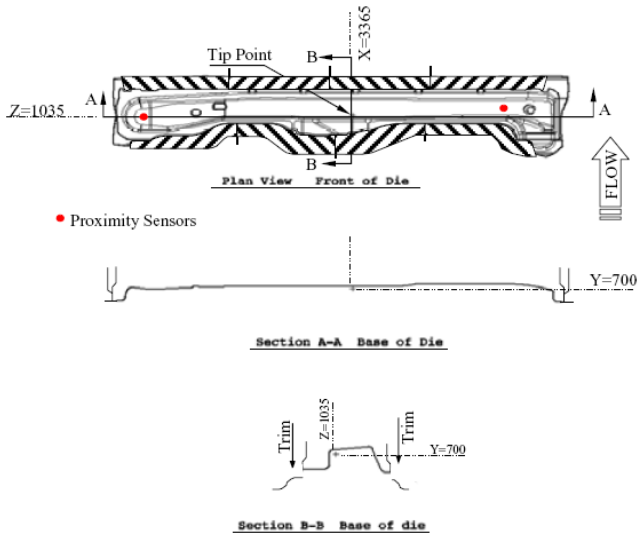
Process Flow:

Developed Blank → 1st Op. → 2nd Op. → 3rd Op. → 4th Op. → 5th Op. → Unload to Conveyor

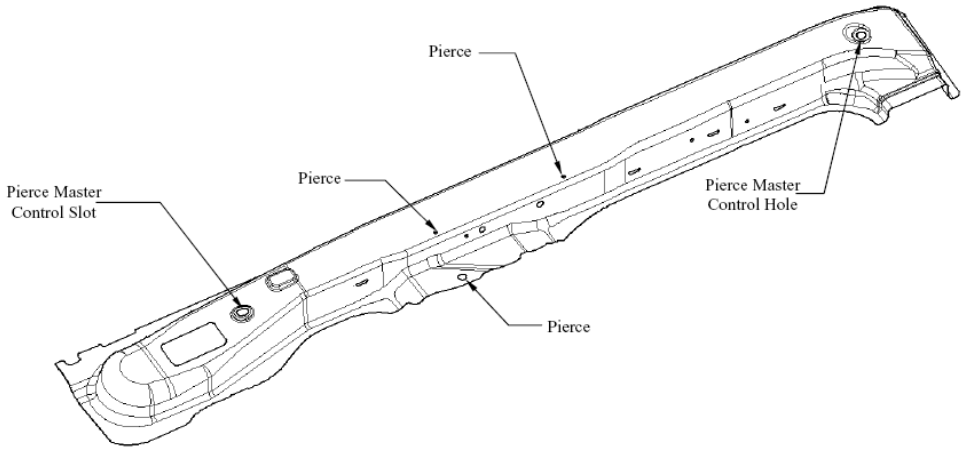
First Die Operation – Toggle Draw



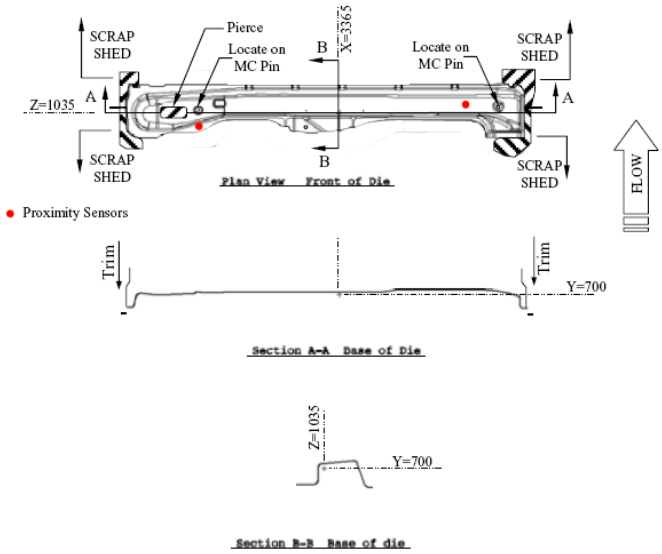
Second Die Operation – Trim & Pierce after Idle Turnover



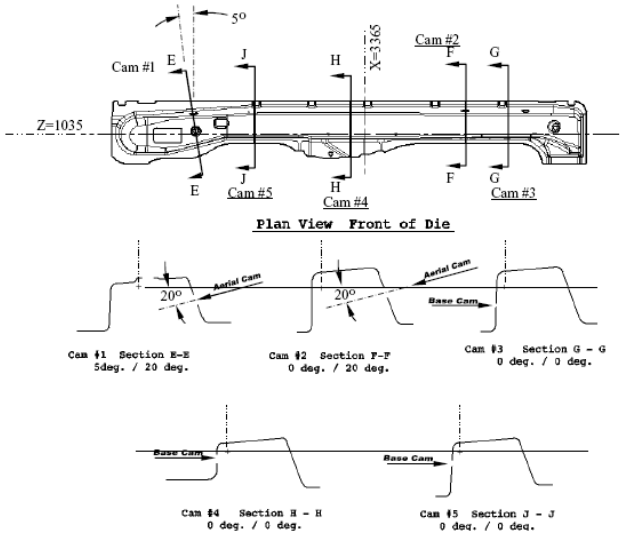
Second Die Operation – Trim & Pierce (continued)



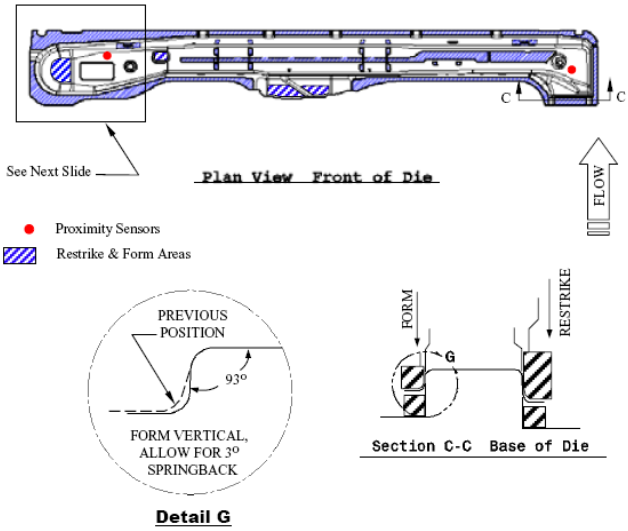
Third Die Operation – Trim, Pierce & Cam Pierce



Third Die Operation – Trim, Pierce & Cam Pierce (continued)

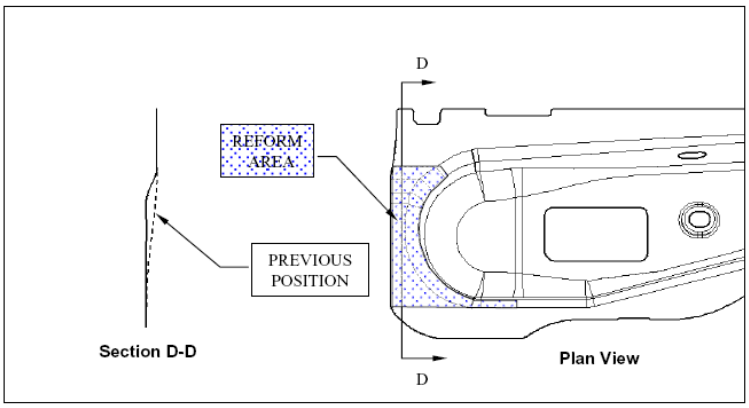


Fourth Die Operation – Form & Restrike



STAMPING PROCESS DESIGN

Fourth Die Operation – Form & Restrike (continued)



FEA FORMABILITY ANALYSIS

CAE analysis are done using Autoform & LS-Dyna software.

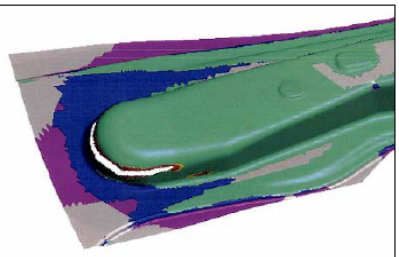
Autoform was used during the CAD draw development stage to optimize all conditions of the non-part die face (blank size, bead force and binder/addenda shape). Once our die engineers are confident that they have reached the optimal non-part conditions, concessions are requested (if needed) to improve part quality. Final Autoform results are used to kick-off die designs.

LS-Dyna was used as our final prove-out tool to optimize all conditions and kick-off die castings.

The results of simulations are shown on the next slides.

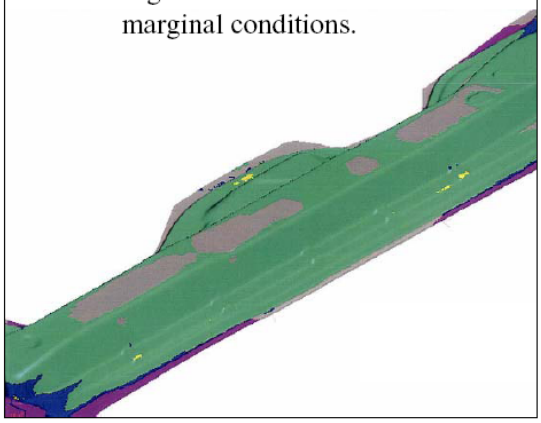
FEA FORMABILITY ANALYSIS

Autoform Simulations



Split was eliminated by shortening the blank and revising the radii and force of the step beads.
(see next slide for part radius concession).

Revising the addenda corrected marginal conditions.



Splits | Excess. thinning | Risk of splits | Safe | Insuff. stretch | Compress | Thicking

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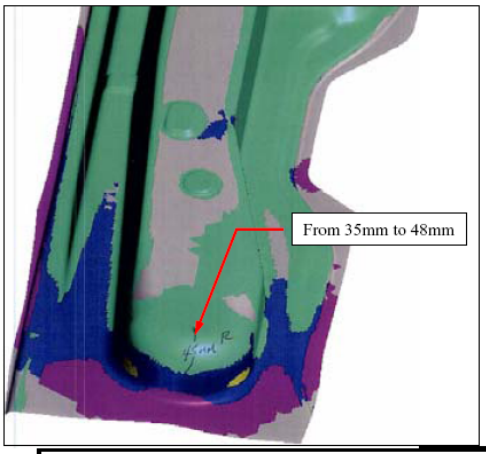
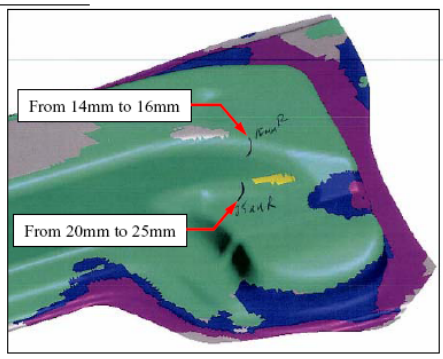
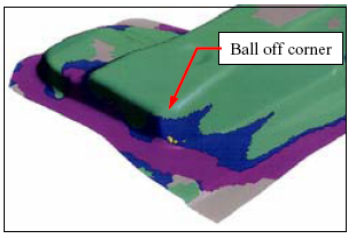
FEA FORMABILITY ANALYSIS

Autoform Simulations







Marginal areas were eliminated by changing the part fillet radii as shown.

Splits | Excess. thinning | Risk of splits | Safe | Insuff. stretch | Compress | Thicking

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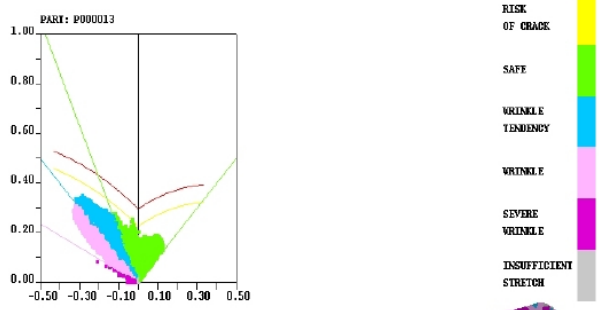
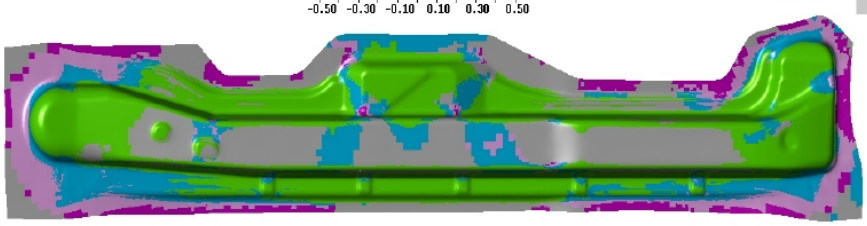
FEA FORMABILITY ANALYSIS

LS-Dyna Simulation

These results were used to proceed beyond die designs

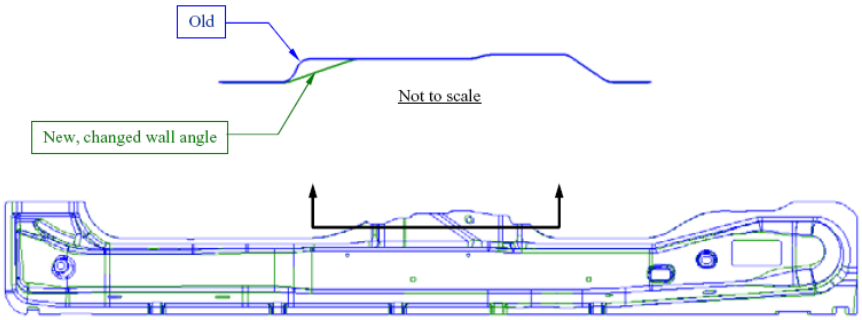
(patterns, castings, machining, construction & tryout).





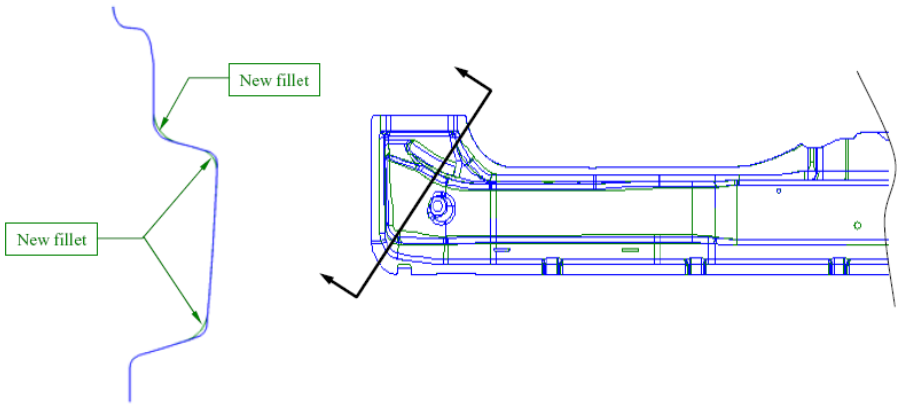
NEGOTIATED GEOMETRY CONCESSIONS

Geometry concessions needed to solve forming problems that were accepted by Product Design



NEGOTIATED GEOMETRY CONCESSIONS

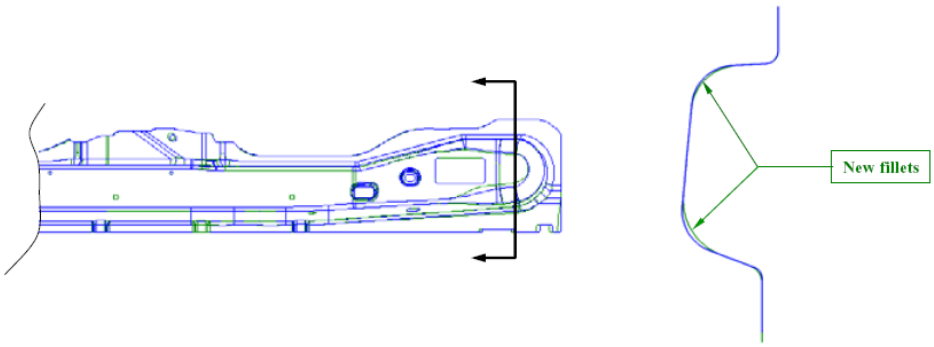
Geometry concessions needed to solve forming problems that were accepted by Product Design



Not to scale

NEGOTIATED GEOMETRY CONCESSIONS

Geometry concessions needed to solve forming problems that were accepted by Product Design



Not to scale

SPRINGBACK COMPENSATION METHODOLOGY

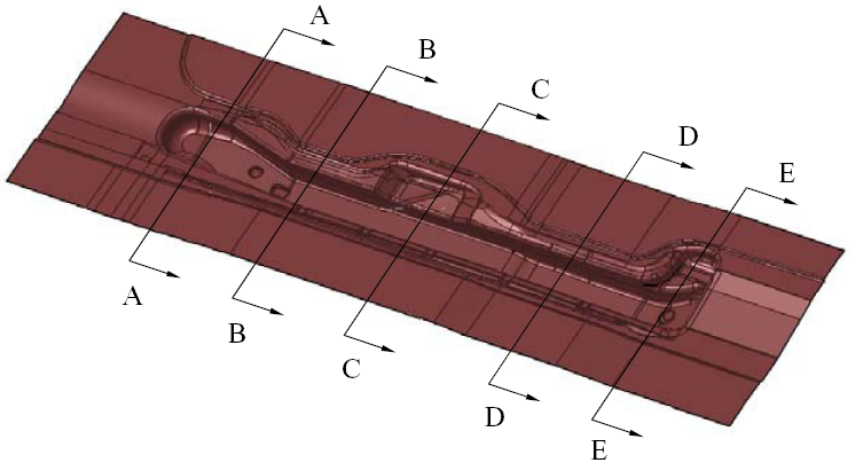
•The approach used to help control springback was to morph the draw dieface using the results from a springback study.

•The study results were determined using CMM data of a physical panel produced from the production tool which was initially cut to nominal.

•The draw panel from the first tryout resulted in a split free panel.

The following slides will show how much morphing was required.

SPRINGBACK COMPENSATION METHODOLOGY



Sections shown on next slide

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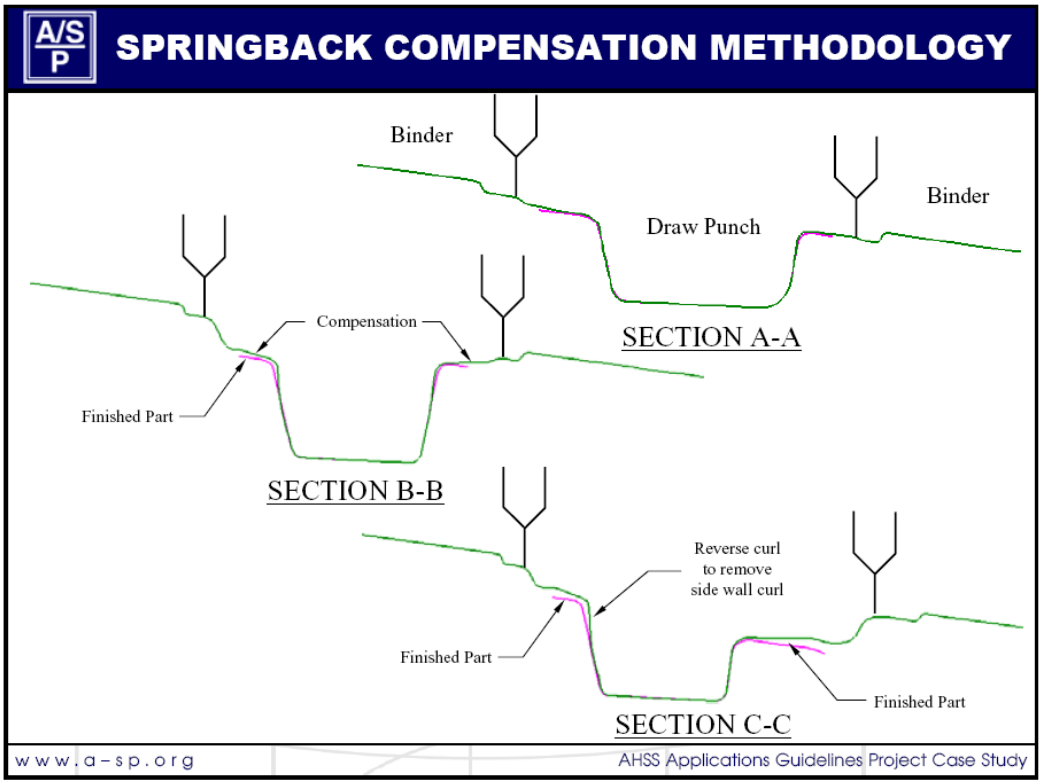
SPRINGBACK COMPENSATION METHODOLOGY
Binder
Draw Punch
Binder
SECTION A-A
Compensation
Finished Part
SECTION B-B
Reverse curl
to remove
side wall curl
Finished Part
Finished Part
SECTION C-C
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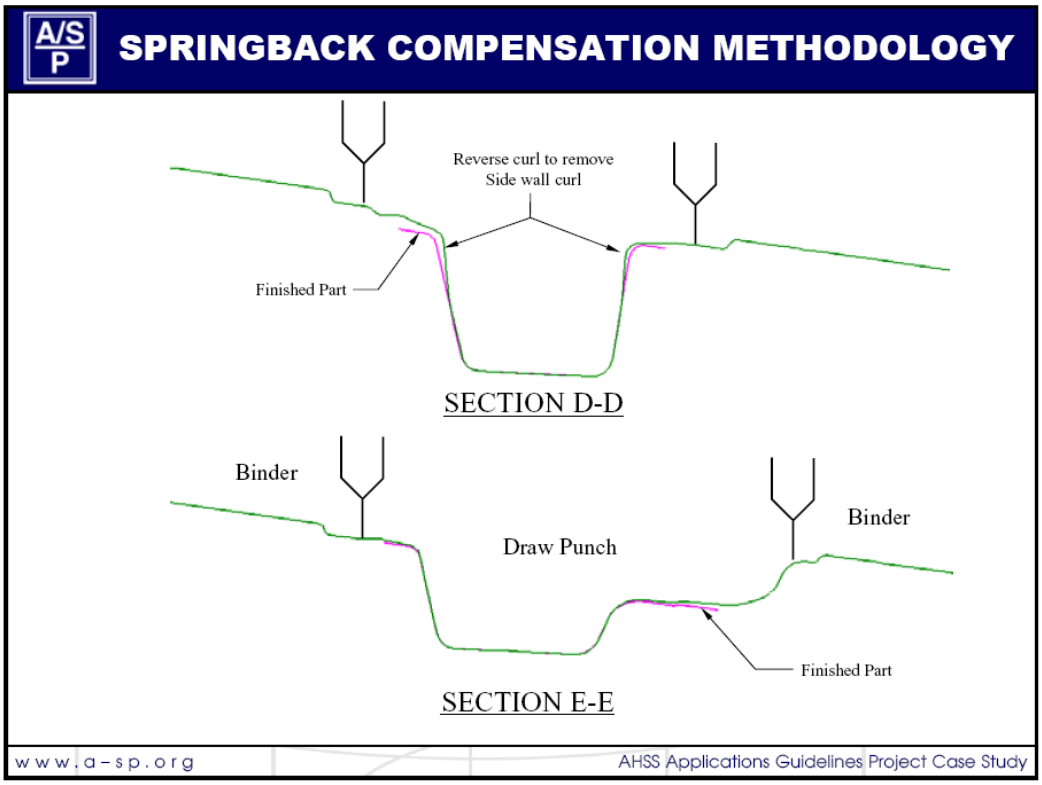
SPRINGBACK COMPENSATION METHODOLOGY
Reverse curl to remove
Side wall curl
Finished Part
SECTION D-D
Binder
Draw Punch
Binder
Finished Part
SECTION E-E
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SPRINGBACK CONTROL HISTORY

Due to springback, twist & side wall curl, an additional four cuts were required to bring the part to design intent.

The basic strategy was to overcompensate the shape to allow the part to springback to nominal.

With each recut there were areas where:

- Compensation was correct (no further change required)
- Did not compensate enough (additional compensation required)
- Overcompensated (reduce amount of compensation)

After four recuts the product was determined to be acceptable.

SPRINGBACK MODEL ACCURACY

- No virtual springback analysis was performed for this tool.
- Compensation was established based on a springback study based on the initial split-free tryout panel.

PRESS LOAD PREDICTION ACCURACY

Die Stage	Press Loads (Tons)				
	Estimate	CAE Prediction	Actual Meas.	Total Available	%
Draw Press	1000	930	790	1800	44
Binder	500	430	361	1000	36
Trim & Pierce	250		162*	1000	16
Trim, Pierce & Cam Pierce	250		170*	1000	17
Form & Restrike	500		352	1000	35

- Estimates are based on formula using material type, material thickness, punch opening perimeter and a factor for depth. Another formula is used for binder tonnage using bead presure.
- CAE prediction are performed using AutoForm
- Actual measurements are from die tryout source, not from production line.

* Includes trim shear

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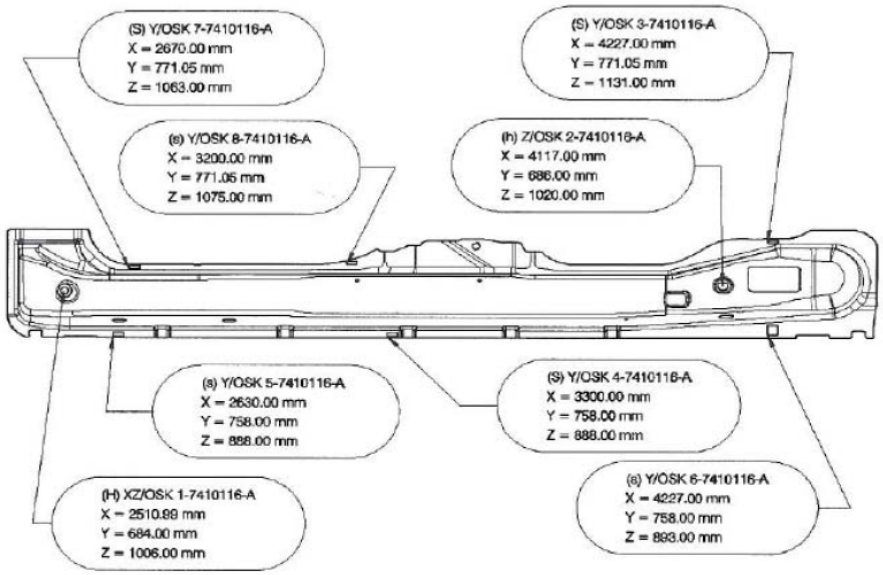
FIXTURING AND CLAMPING



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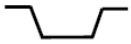
POST-LAUNCH EXPERIENCE & LESSONS LEARNED

Production die issues -

- Lower die (solid lower) cracked during production
- Root cause determined to be unbalanced "hat section" design

- Lower die cavity has been re-designed to a more robust condition
- Future product designs to be "balanced hat"



Case Study Summary #11

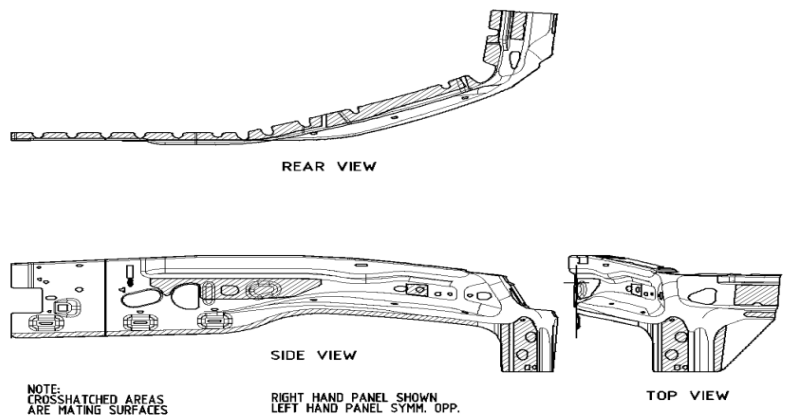
Part Name	PNL. - BACK INSIDE SIDE	**Material/Grade :**	DP600T/350Y	**Gage :**	1.5mm
Coating :	HD60G60G	**URL for Full Case Study:**	www.a-sp.org/publications.htm		
Spring-back/Twist Countermeasures:	Multiple die recuts required to achieve acceptable part quality. (overseas vendor)				

Manufacturing Process

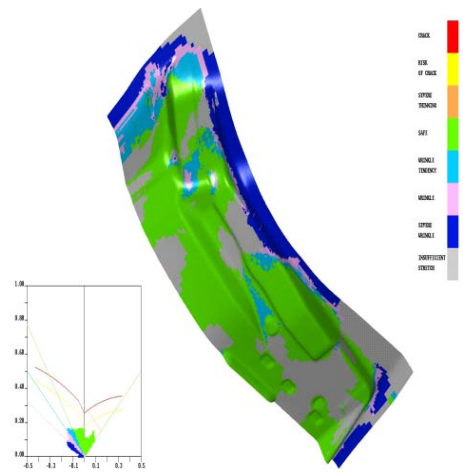
No. of Dies-	**5**	Draw	Trim / Prc./ Cam Tr.	Flg, / Tr. / Cam Tr	Tr. / Prc. / Cam Prc.	Flg. / Restrike		

Diagrams / Illustrations

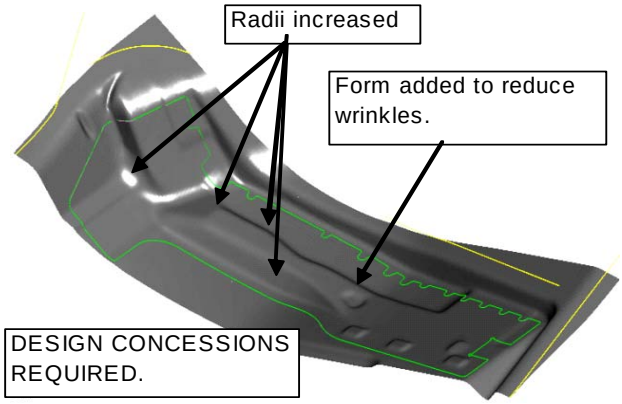
Part Geometry

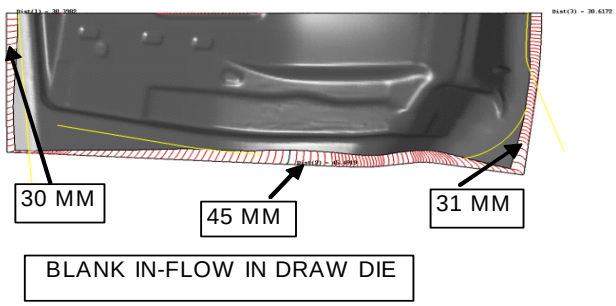


Forming Limit Diagram



Die Construction Considerations

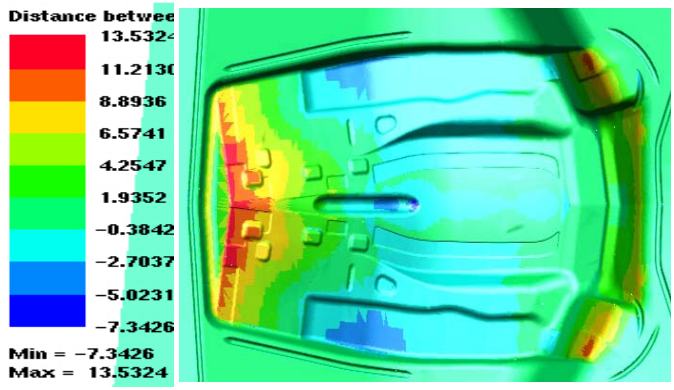




Notes

- CAE analysis was done using Autoform and LS-Dyna software.
- Autoform was used during the CAD draw development stage.
- Concessions were requested to improve part quality.
- Final Autoform results were used to start die designs.
- LS-Dyna was used as the final prove-out tool to optimize all conditions and begin die casting construction.

Springback Compensation Methodology



Die Morph vs. Nominal - Normal Distance, above + below -

Die originally cut to nominal and recut after first panel.
Multiple recuts required to achieve the desired part quality.
Number of recuts unknown due to overseas vendor tryout.

Additional Information -

M2 overweld applied at high wear radii areas.
No unusual production concerns due to AHSS material.

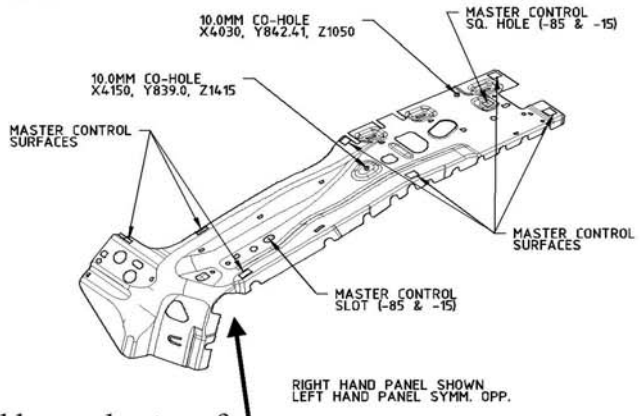
Case Study #11: Panel Back Inside Side

Eric Frevik
Die Engineering Manager
Ford Motor Company
www.ford.com
efrevik@ford.com

PART DESCRIPTION

Part Name: Panel Back Inside Side

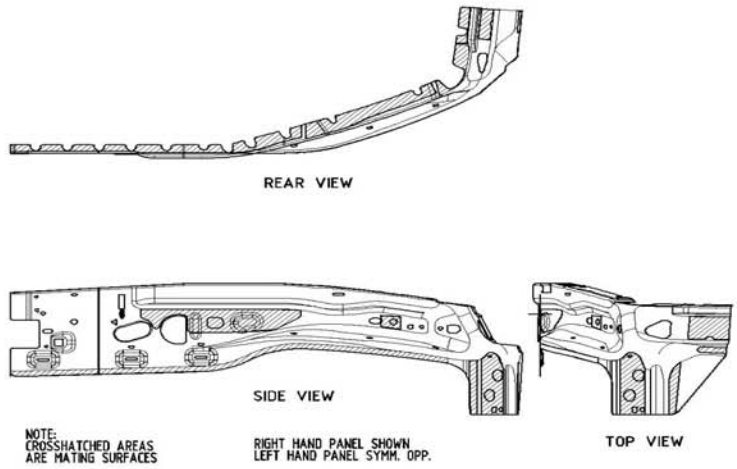
- depth of draw = 75 mm



- Formability limited by angle at roof rail header joint

PART DESCRIPTION

Part Name: Panel Back Inside Side

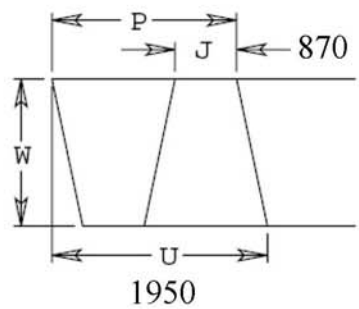


MATERIAL DESCRIPTION

Steel Grade: DP 600
Coating: 60G60G HD
Gauge: 1.50 mm
Blank Width: 1520 mm (W)
Blank Pitch: 1880 mm (P)
Blank Shape: Trap

Same steel vendor used for die development and production steel supply

Actual Material Properties:
(used for tryout & production)
Yield Strength: 385 MPa, 55.8 ksi
Tensile Strength: 630 MPa, 91.4 ksi
Total Elongation: 24.2%
n-value (4-6%): 0.199
n-value (5-15%): 0.167



1520 x 1880 = 4 parts

PRESS LINE CONSTRAINTS

Tandem Press Line

Press #1: Double Action Toggle, 120 x 84, Inner Ram 1500T, Outer Ram 800T
Press-applied binder pressure (outer slide)

Press #2: Straight Side, 108 x 84, 800T, Nitro Upper Pad Pressure
Press #3: Straight Side, 108 x 72, 1000T, Nitro Upper Pad Pressure
Press #4: Straight Side, 108 x 72, 1000T, Nitro Upper Pad Pressure
Press #5: Straight Side, 108 x 84, 800T, Nitro Upper Pad Pressure

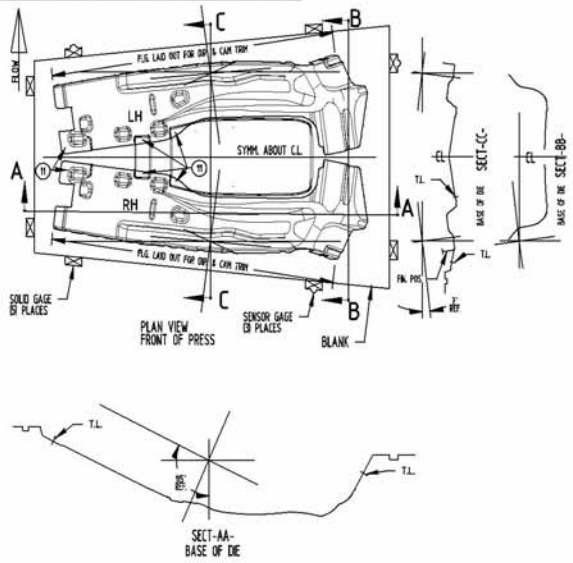
STAMPING PROCESS DESIGN

Process Overview
1st Operation: Double Action Toggle Draw
Part Turnover
2nd Operation: Trim, Pierce, Cam Trim & Cam Pierce
3rd Operation: Flange, Trim, Cam Trim, Cam Form & Separate
4th Operation: Trim, Pierce & Cam Pierce
5th Operation: Flange, Restrike & Stamp

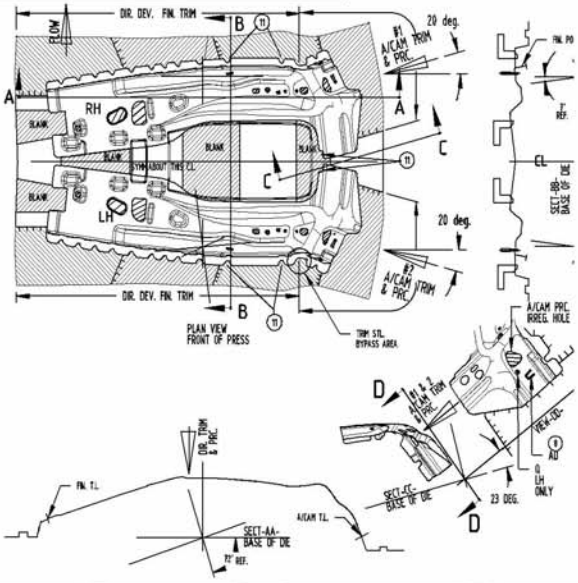
Process Flow:

Trap Blank → 1st Op. → 2nd Op. → 3rd Op. → 4th Op. → 5th Op. → Unload to Conveyor

First Die Operation – Form Die

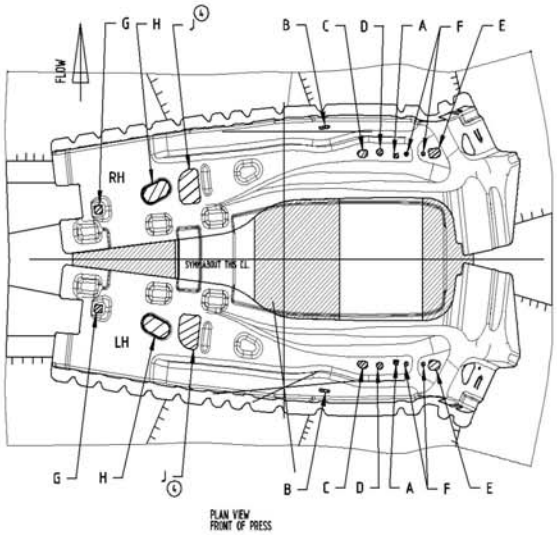


Second Die Operation – Trim Die



STAMPING PROCESS DESIGN

Second Die Operation – Trim Die (cont.)



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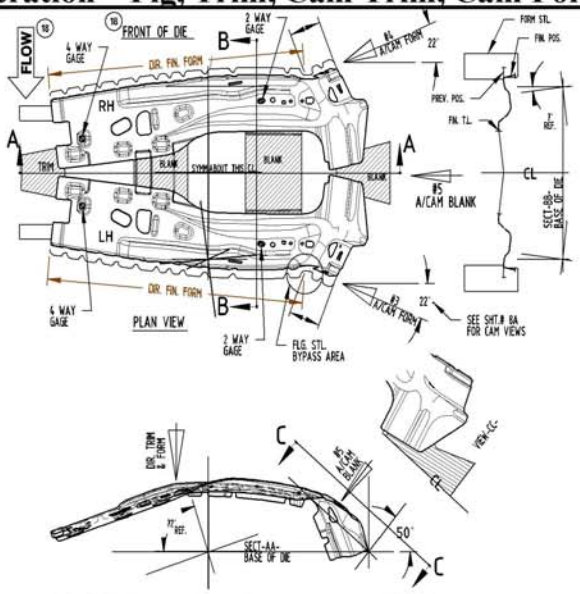
STAMPING PROCESS DESIGN

Third Die Operation – Flg, Trim, Cam Trim, Cam Form & Separate



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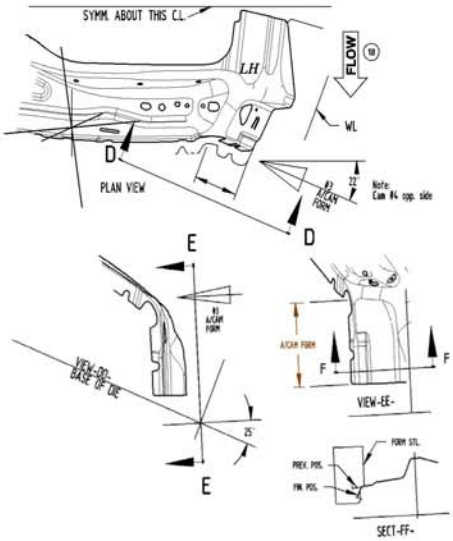
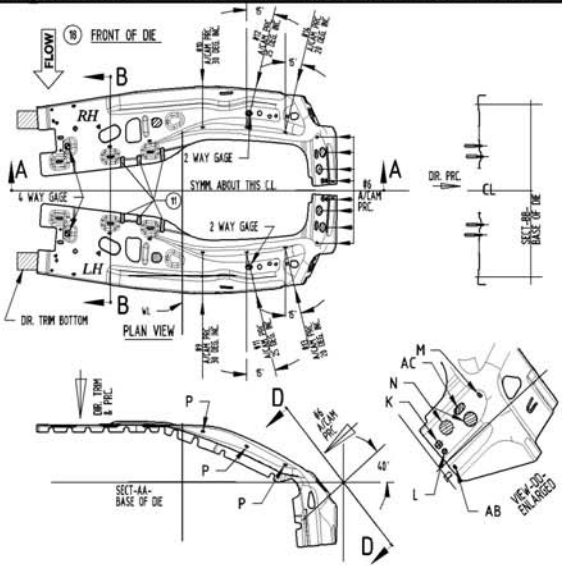
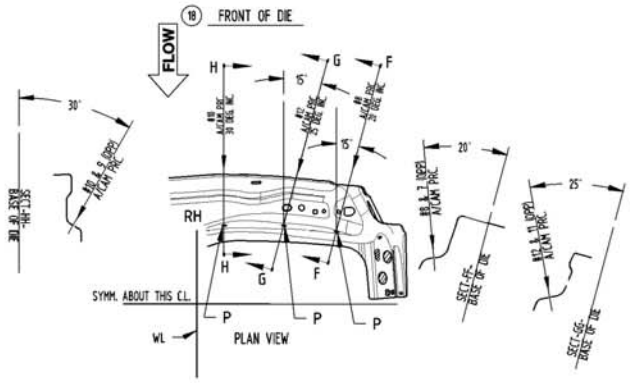
Third Die Operation – Flg, Trim, Cam Trim, Cam Form & Separate (cont.)



Fourth Die Operation – Trim, Pierce & Cam Pierce

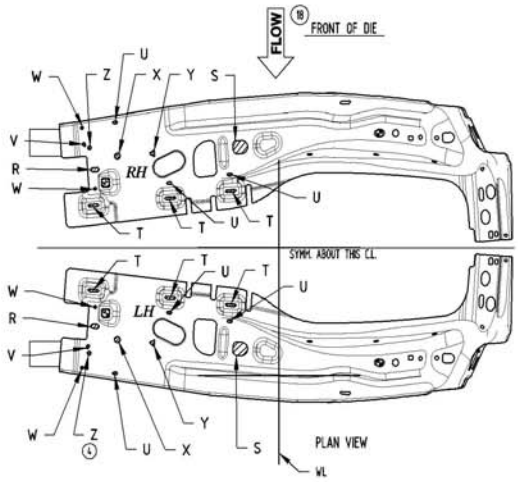


Fourth Die Operation – Trim, Pierce & Cam Pierce (cont.)



A/S P
STAMPING PROCESS DESIGN

Fourth Die Operation – Trim, Pierce & Cam Pierce (cont.)



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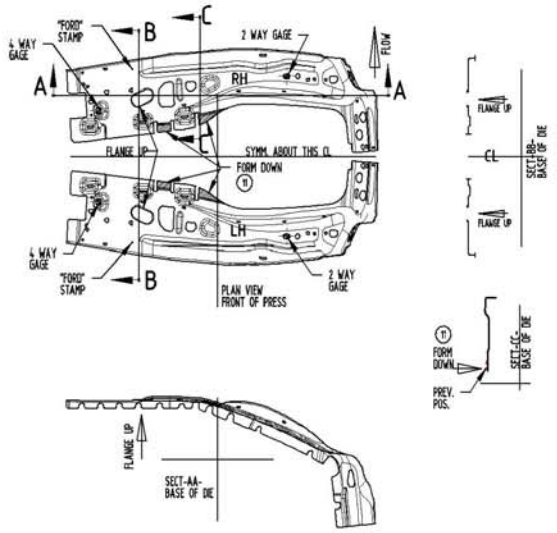
STAMPING PROCESS DESIGN

Fifth Die Operation – Flange, Restrike & Stamp



FEA FORMABILITY ANALYSIS

CAE analysis are done using Autoform & LS-Dyna software.

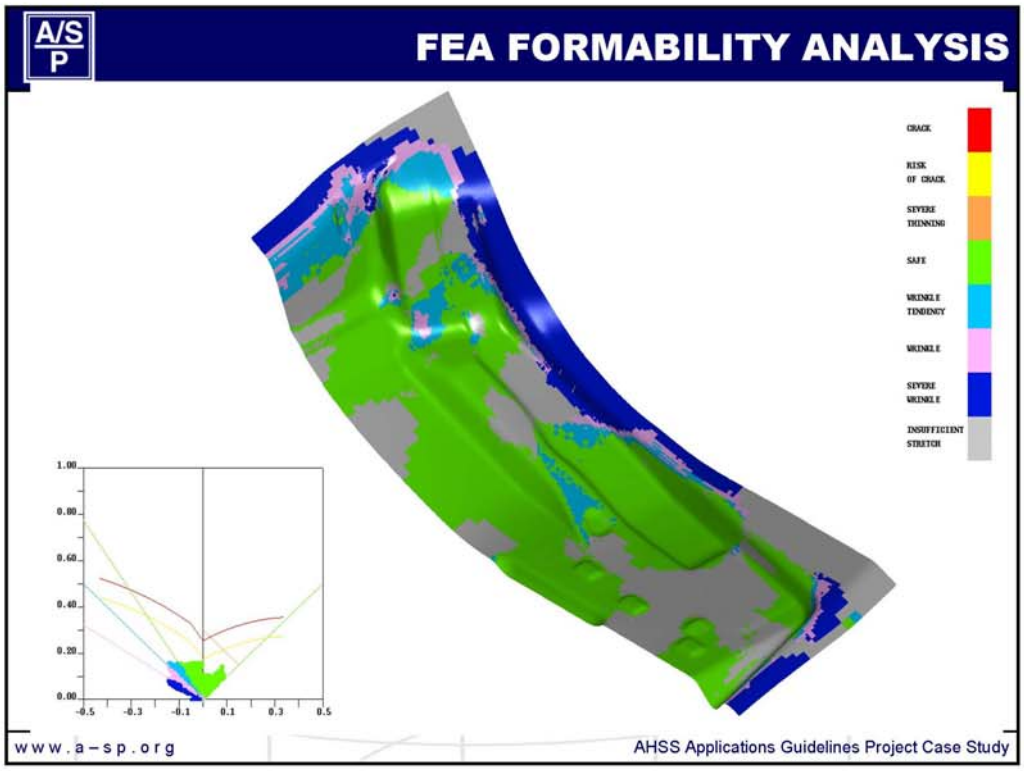
Autoform was used during the CAD draw development stage to optimize all conditions of the non-part die face (blank size, bead force and binder/addenda shape).

Concessions are requested to improve part quality.

Final Autoform results are used to kick-off die designs.

LS-Dyna was used as our final prove-out tool to optimize all conditions and kick-off die castings.

The results of simulations are shown on the next slides.


FEA FORMABILITY ANALYSIS
CRACK
RISK OF CRACK
SEVERE THINNING
SAFE
WRINKLE TENDENCY
WRINKLE
SEVERE WRINKLE
INSUFFICIENT STRETCH
1.00
0.80
0.60
0.40
0.20
0.00
-0.5
-0.3
-0.1
0.1
0.3
0.5
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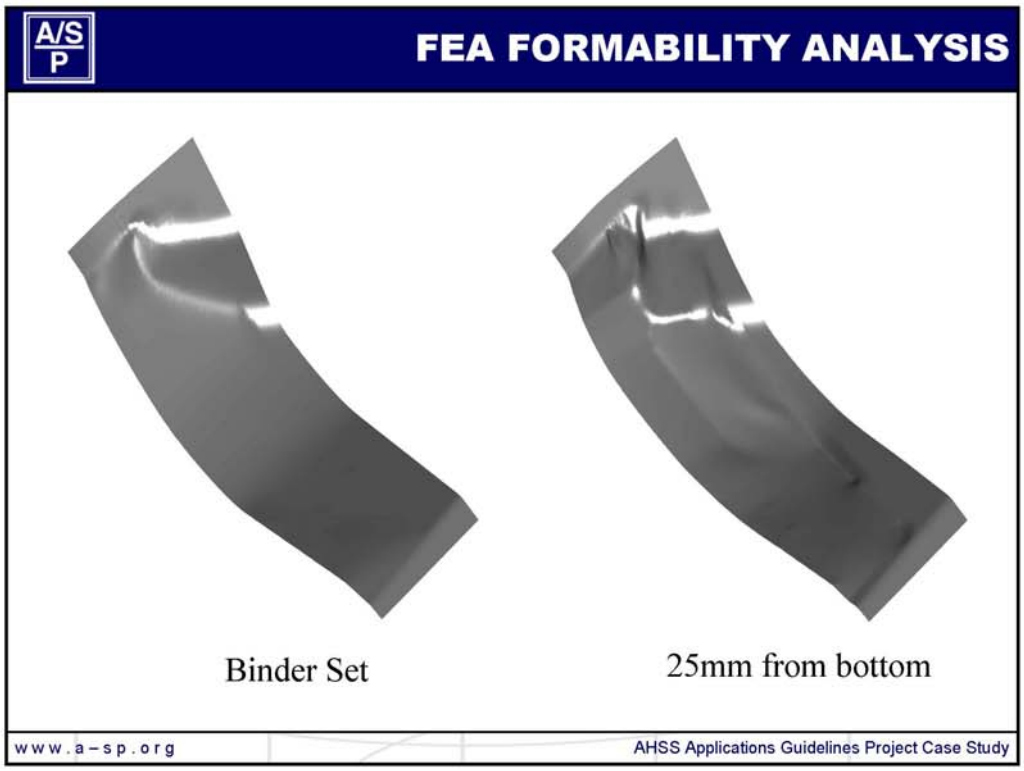
FEA FORMABILITY ANALYSIS
Binder Set
25mm from bottom
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FEA FORMABILITY ANALYSIS

15 mm from bottom

10 mm from bottom

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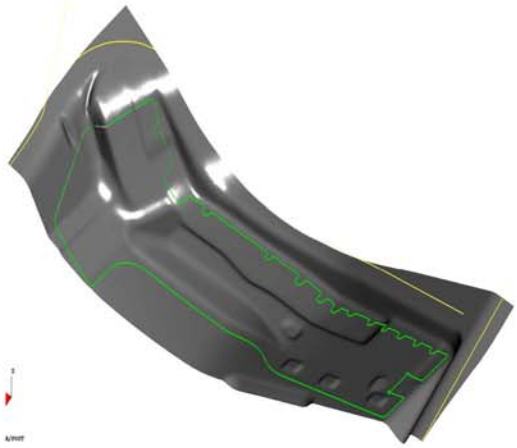
FEA FORMABILITY ANALYSIS

5mm from bottom



bottom

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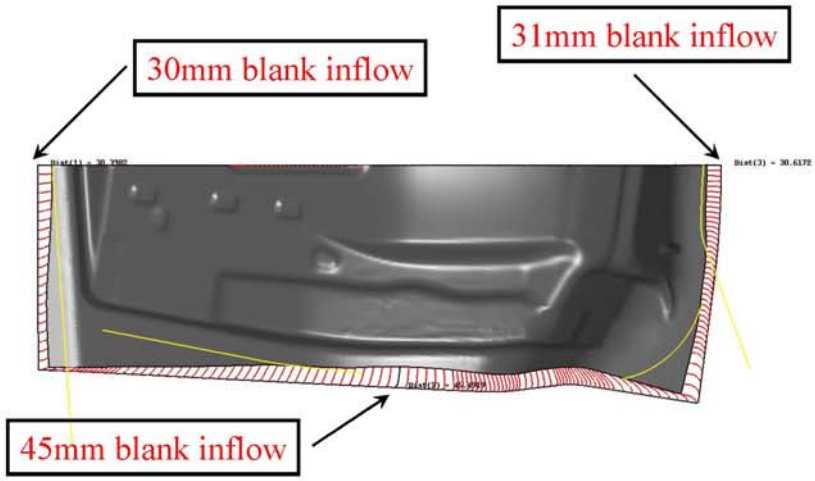
FEA FORMABILITY ANALYSIS



Index	NodeID	MOVEPOINT-XY	x-dir	y-dir	z-dir
1	1	+3.0290E+01	3.0290E+01	0.0000E+00	0.0000E+00
2	1735	+4.5495E+01	3.1869E+00	4.4571E+01	0.0000E+00
3	154	+3.0617E+01	-3.0617E+01	0.0000E+00	0.0000E+00

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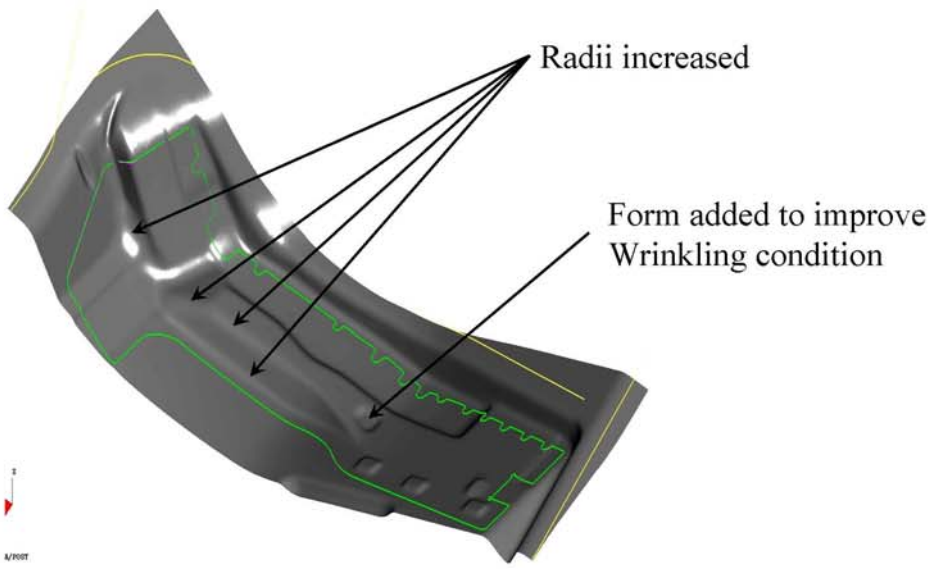
NEGOTIATED GEOMETRY CONCESSIONS



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SPRINGBACK COMPENSATION METHODOLOGY

Describe approach to controlling springback:

- Die originally cut to nominal and recut after First Panel to Gage.
- Multiple re-cuts were required to achieve the desired part quality

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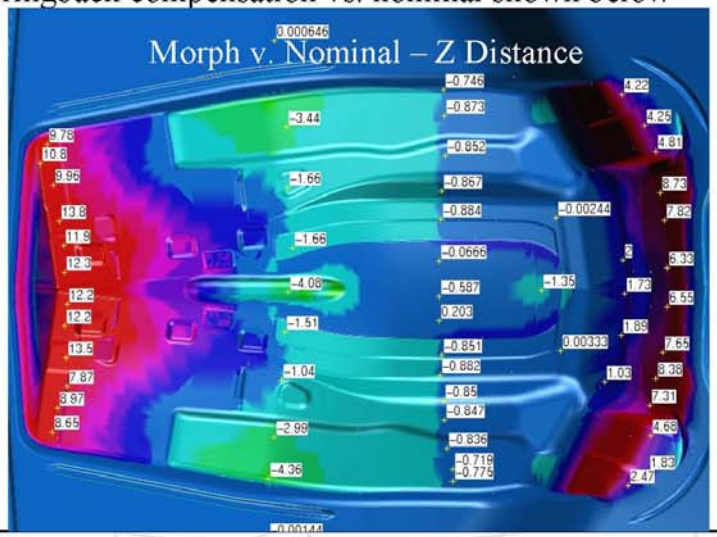
SPRINGBACK CONTROL HISTORY

- No. of re-cut is unknown due to vendor tryout by third party overseas
- Final springback compensation vs. nominal shown below



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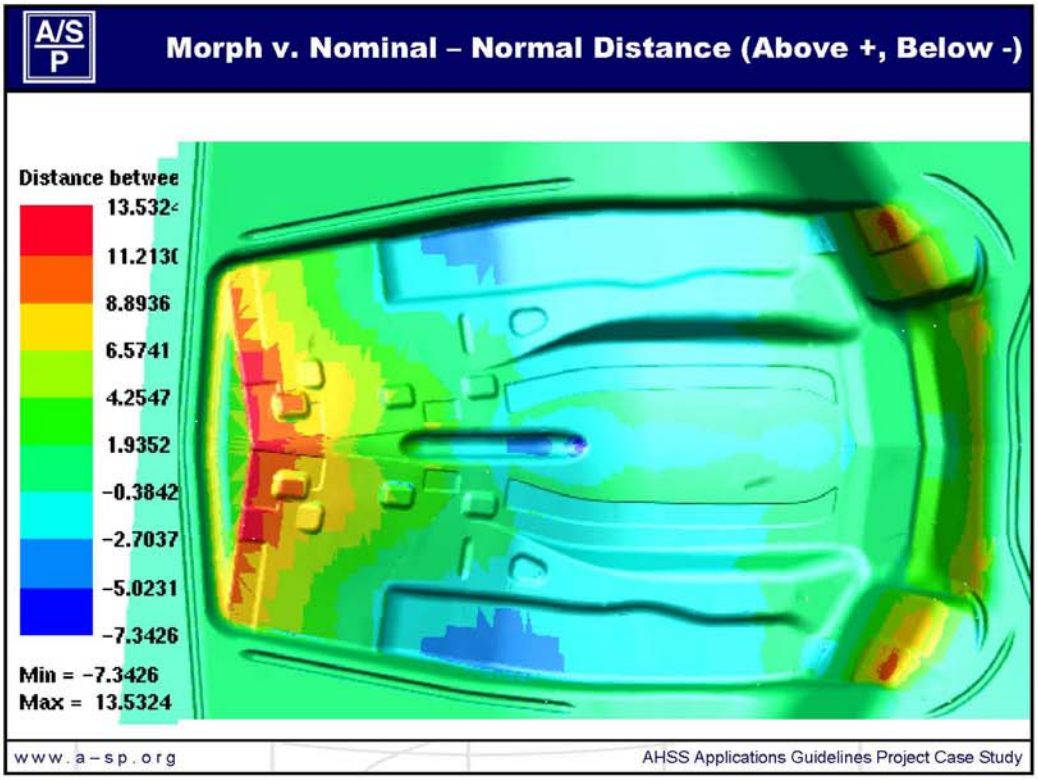
A/S P
Morph v. Nominal – Normal Distance (Above +, Below -)
Distance betwee
13.532
11.213
8.8936
6.5741
4.2547
1.9352
-0.3842
-2.7037
-5.0231
-7.3426
Min = -7.3426
Max = 13.5324
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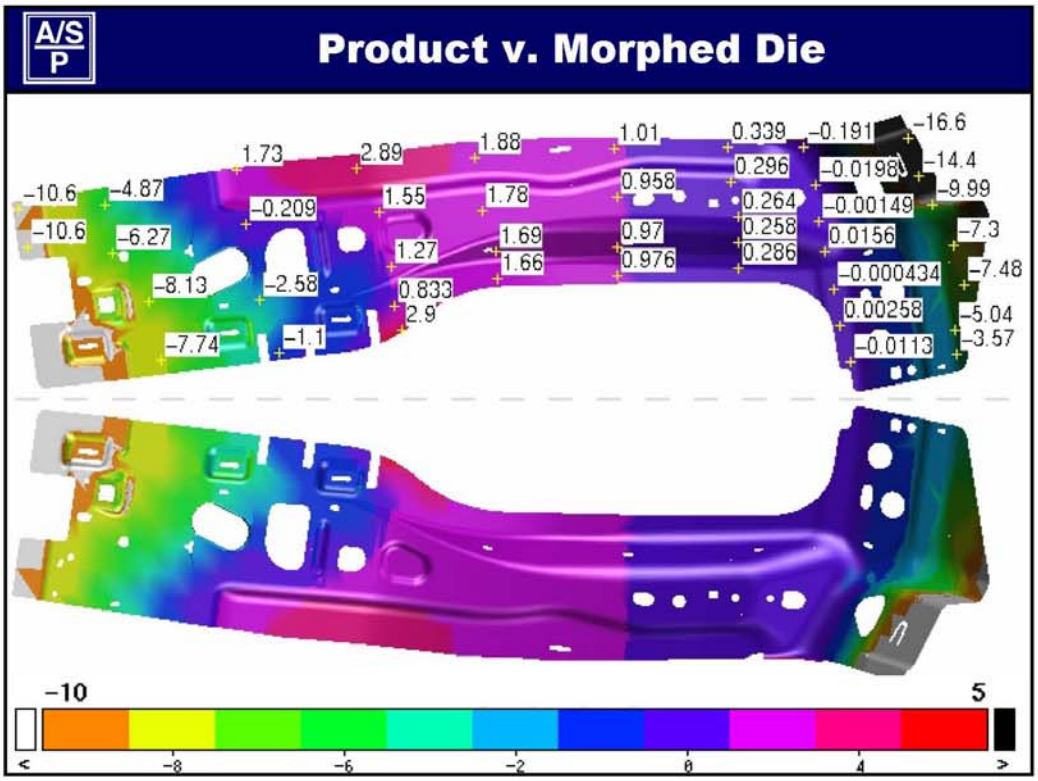
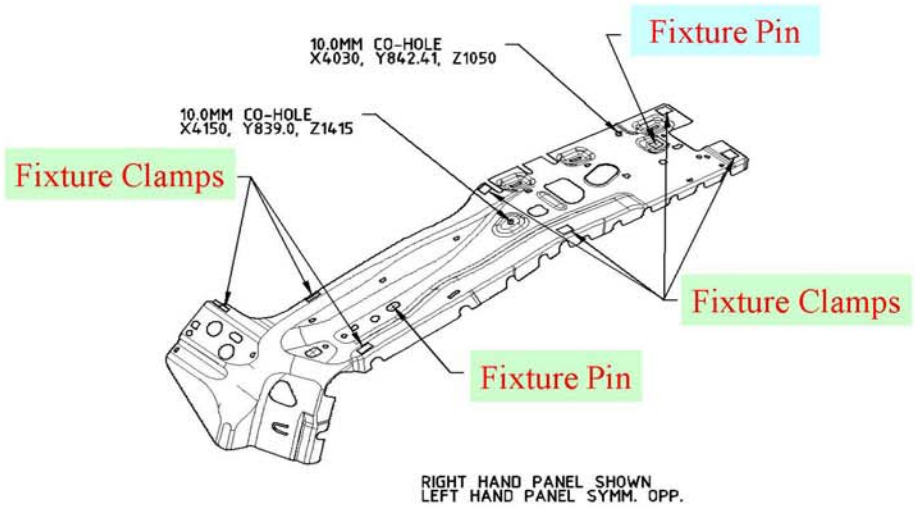

A/S P
Product v. Morphed Die
-10
5
<
-8
-6
-2
0
4
>

Fixturing and Clamping



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PRESS LOAD PREDICTION ACCURACY

Die Stage	Press Loads (Tons)				
	Estimate	CAE Prediction	Actual Meas.	Total Available	%
Forming Press	1200T	N/A	1340T	1500T	
Binder	350T		300T	800T	
Trim & Pierce	135T	N/A	*	800T	
Flange and Pierce	350T	N/A	*	1000T	
Trim, Pierce & Cam Pierce	150T	N/A	*	1000T	
Flange & Restrike	150T	N/A	*	800T	

* No tonnage monitors on production line die presses

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POST-LAUNCH EXPERIENCE

Production Feedback

- No unusual production concerns due to material.
- Slug shedder punches installed on holes smaller than 10mm.

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LESSONS LEARNED

Tooling Development Revisions:

- M2 Over-weld process was revised to identify high wear radii analytically.
- Previous M2 Over-weld process required all radii to be over-welded and re-machined.
- Standard revised to use slug shedder punches for holes < 10mm.

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Case Study Summary #12

Part Name	REINF.-BAFFLE ROCKER	**Material/Grade :**	DP 800T/500Y	**Gage :**	2.0mm
Coating :	Hot Dipped Galvanized	**URL for Full Case Study:**	www.a-sp.org/publications.htm		

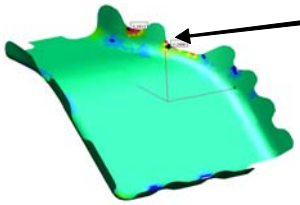
Spring-back/Twist Countermeasures: Sidewalls must be a minimum of 6 degrees open to allow overbend compensation.

Manufacturing Process

No. of Dies- 6	Blank	Draw	Cam Trim	Separate	Trim & Cam Prc.	Restrike

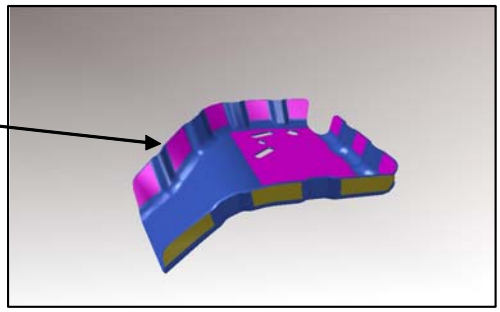
Diagrams / Illustrations

Part Geometry

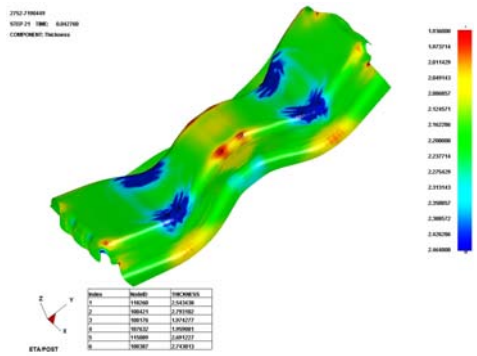


Part as originally designed with notches. Progressive / flange die process. Splits at notches made process impractical.

Part as redesigned. Draw die process with cam trim of sidewalls. Manual part transfer.

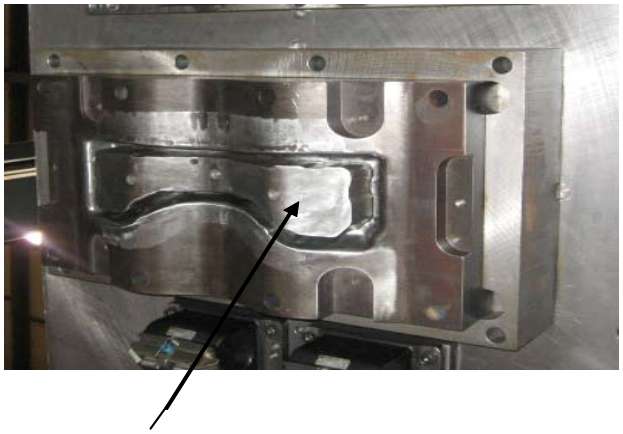


Forming Limit Diagram



Forming Limit Study showing excessive thinning and wrinkles in some areas.

Die Construction Considerations



Upper pressure pad added to draw die to control wrinkles.

Overbend added to all sidewalls in restrike die.

Notes

Flange die replaced with draw operation to eliminate splits.

Upper pressure pad added to draw die to reduce wrinkles.

Overbend was added to all part walls in the restrike die for springback compensation.

The draw die radius was reduced to eliminate wrinkles. The best result was achieved with a 2.0 mm radius.

Die Tryout Information

Draw die radius reduced to 2.0 mm to eliminate wrinkles.

Upper pad pressure increased from 3 ton to 10 ton for control of wrinkles. The 2.0 mm DP 800T/500Y stamping shows no signs of part inversion from opposing pads in die. Therefore, a lower pad delay system was not required.

No draw beads were used. Material gauge and strength did not allow sufficient gas cylinder pressure to set beads.

Case Study #12: Reinforcement Baffle Rocker R/L

J.Phil Pensom
Director of Engineering
Richard Tool & Die Corporation
Rtdcorp.com
ppensom@rtdcorp.com

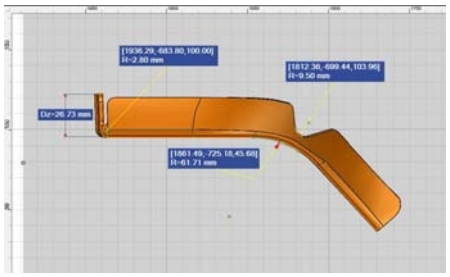
Part History

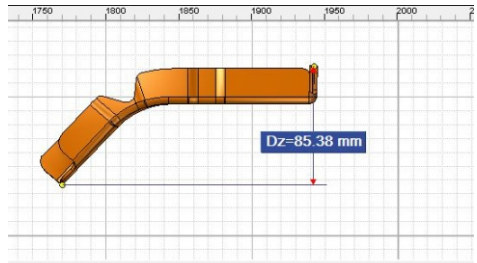
- Project quoted to a similar process and material as previous vehicle.
- Material changed at the release level from HC210BH 2.3mm thick with an elongation in excess of 30% as used on the previous vehicle to CR950DL 2.2mm thick with an elongation not exceeding 12% at the "F" Level for the New Vehicle Project.
- The material spec changed again at the "H" level to HD680C ZE75/75 2.2mm thick prior to design kick off.
- Due to the HD680C ZE75/75 2.2mm thick being commercially unavailable, the spec was later changed to DP 500/800 at 2.0mm with an elongation not exceeding 10%.

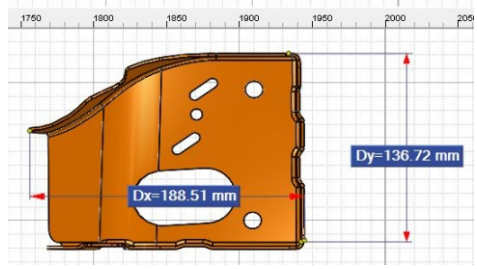
Previous Part

Old Die Process with Higher Strength Material

PART DESCRIPTION







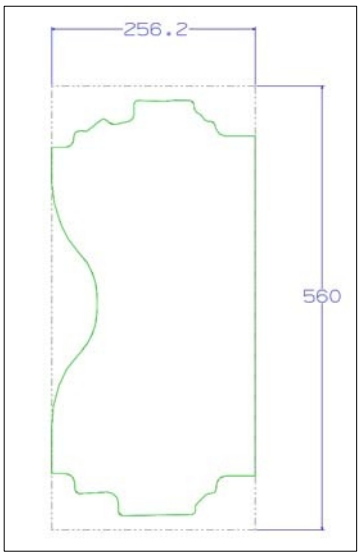
Part Name: Reinforcement Baffle Rocker R/L

- Critical radius is the 9.5mm radius at the bottom of the side flange cut out.
- A form and flange process was chosen due to this radius.
- This decision was determined to be the root cause of process failure.

MATERIAL DESCRIPTION

Steel Grade:	DP 500/800
Coating:	HDG
Yield Min:	500MPa
Tensile Min:	800MPa
Gauge:	2.00 mm
Blank Width:	560 mm
Blank Pitch:	256.2 mm
Blank Shape:	Partially developed
Lubrication:	Mill oil only

Material Properties as Measured
Yield: 698MPa
Tensile: 878MPa
Uniform Elongation: 8.6%*
Total Elongation: 14.4%*
n-value (4-6%): 0.113
n-value (5% - U.E.): 0.099
R-value: 0.66

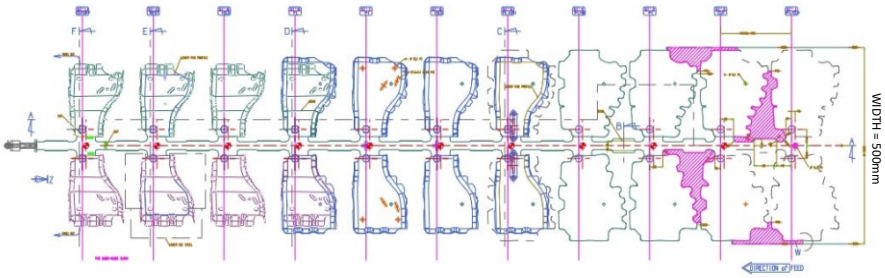


*NOTE: ASTM Regular, A370, E8 – 50.8mm gauge length

Original Process Designed and Built

100	90	80	70	60	50	40	30	20	10	05
CUT-OFF	RESTRIKE	IDLE	'-*/(& %08/	1*&3S&	IDLE	FLANGE UP	FLANGE TAB	PIERCE	NOTCH	PIERCE & NOTCH

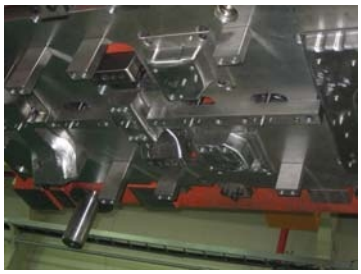
PITCH = 190mm



FRONT OF PRESS
800 TON ERFURT

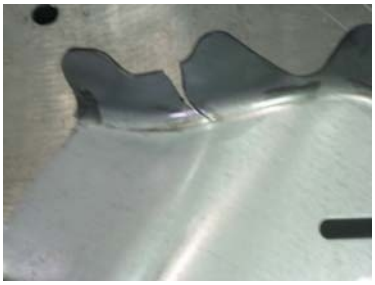
FLOW

Original Process Designed and Built



Results From Progressive Die



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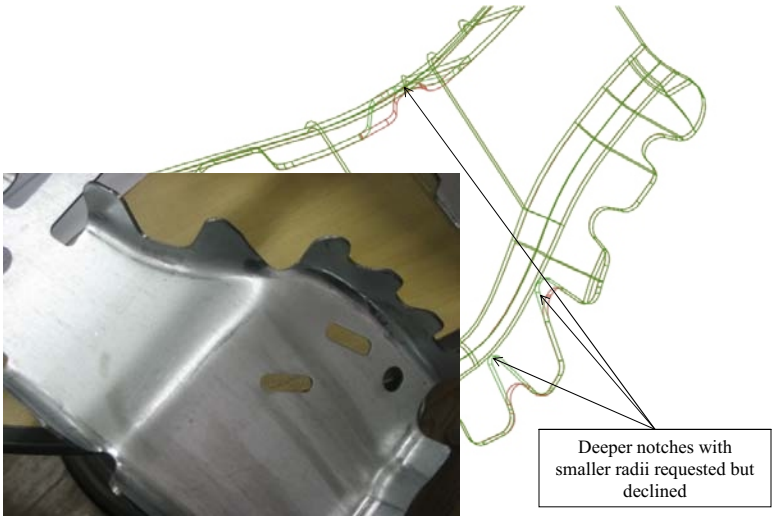
Product Changes Requested



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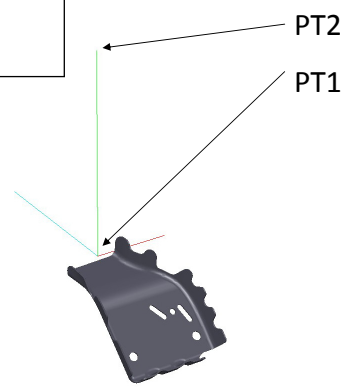
Formability Analysis

AS CURRENT PROCESS

PART NAME:	Reinforced Baffle Rocker L/R
ISSUE LVL:	M1B
MATL GRADE:	DP 500/800
MATL THICKNESS:	2.0mm
BLANK DIMS :	-
BINDER TVL:	45.5mm (FLANGE)
SIM PROCESS OP10	FLANGE UP
SIM PROCESS OP20	FLANGE DOWN

Draw Tooling Approach line=
Point 1
X= 1762.45
Y= -755.49
Z= 28.05
Point 2
X= 1540.03
Y= -749.13
Z= 229.26

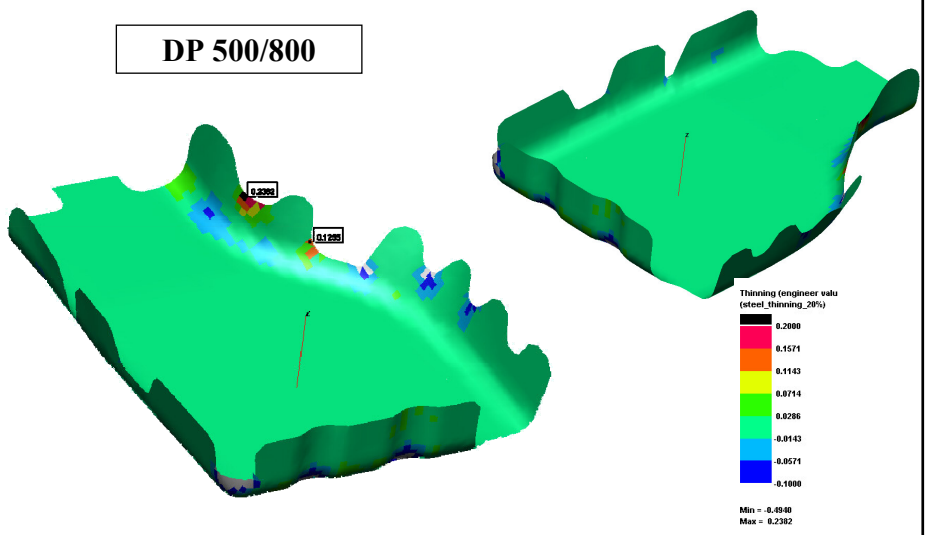
DP 500/800



Formability performed after die was completed. Formability was not performed at the time of material change.

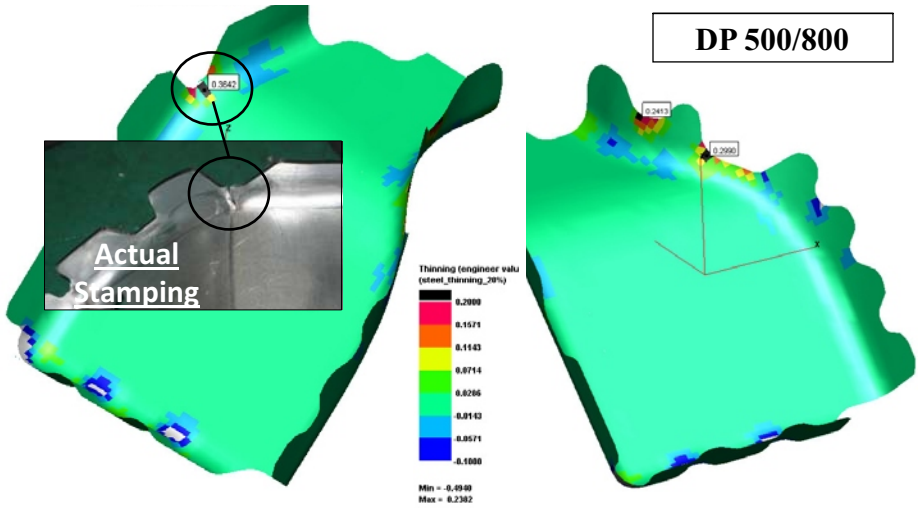
OP40 Flange Up Thinning

DP 500/800



Thinning over 20% highlighted in black

OP70 Flange Down Thinning

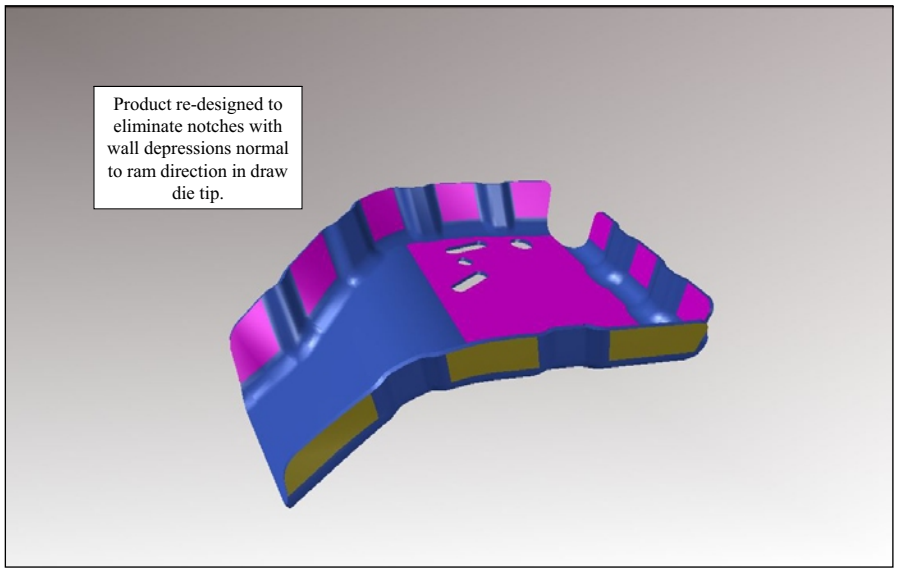


Thinning over 20% highlighted in black

Tooling Supplier Proposed New Process

- Upon review of the process simulations and the inability to adapt the progressive die to a draw process, Tooling Supplier proposed a manual hand transfer process
- Many different options studied by both the Tooling Supplier and Tier 1 Customer with only one reliable solution
- Product required to be drawn past the trim line and cam trimmed to assure no edge splitting on trim line
- Scalloped trim line not feasible for cam trim
- Released for production

Product Release Changes



STAMPING PROCESS DESIGN

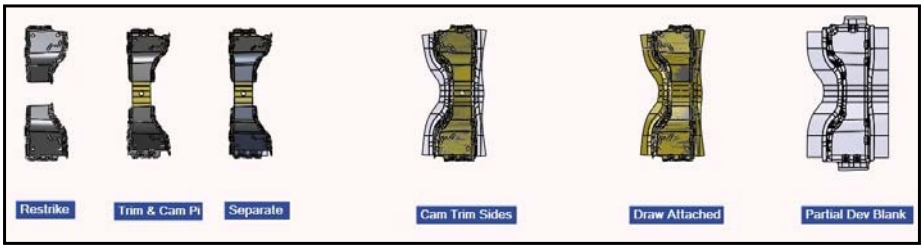
Re Designed Process Overview

•Forming Process Type: Manual (Hand Transfer) Tandem 800 Ton 4000 x 2000

•Die Material: All dies were uncoated fully hardened D2 steel

Process Flow:

Re Strike ← Trim & Cam Pierce ← Separate ← Cam Trim ← Draw ← Blank ← Shear

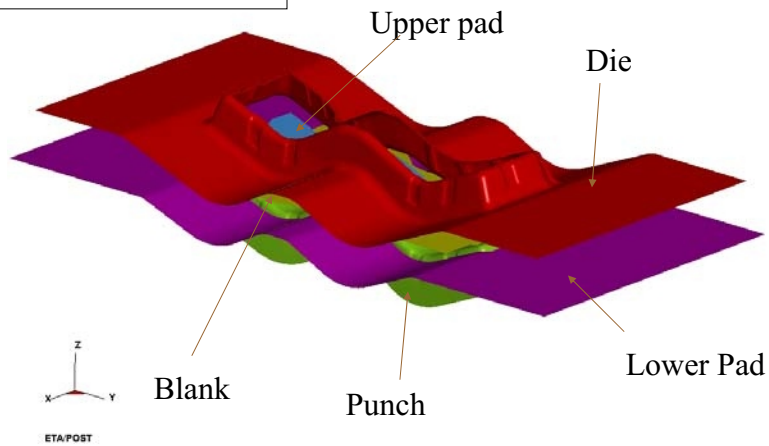


Flow

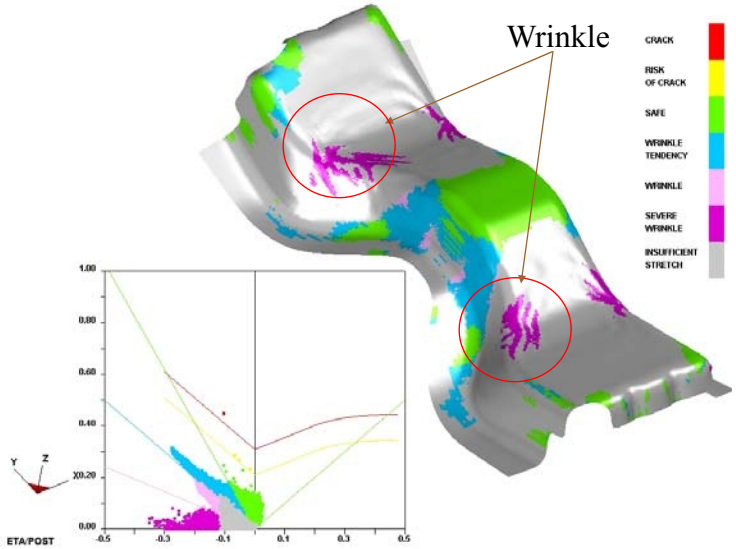
Formability Analysis Draw Tools

Binder force:10 tons

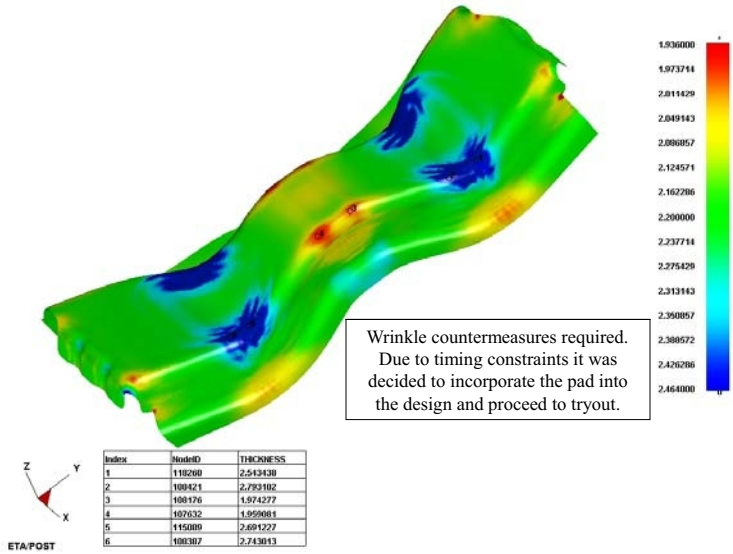
The binder was shaped to match the punch shape exactly and the pad was also matched and timed to the binder contact.



Formability Analysis



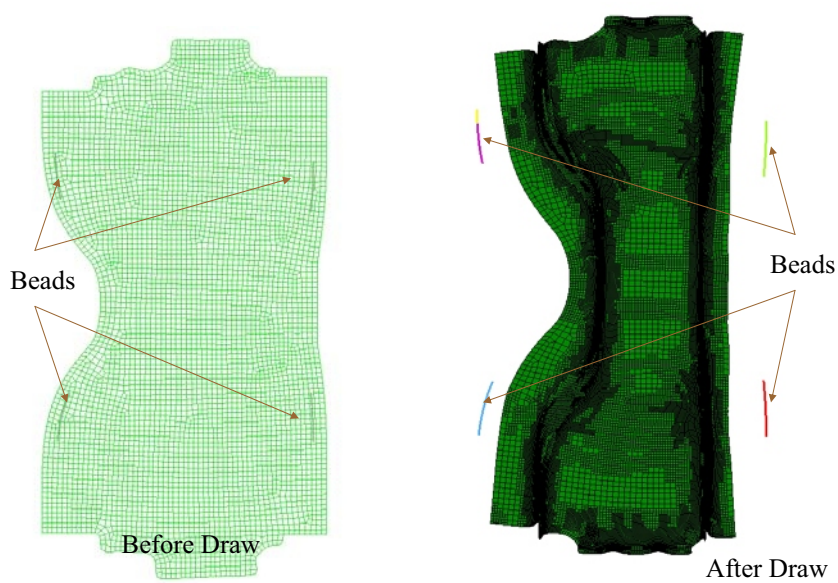
Formability Analysis – Thickness Map



Index	NodeID	THICKNESS
1	118260	2.513438
2	108421	2.793102
3	108176	1.974277
4	107632	1.959081
5	115089	2.691227
6	108307	2.743013

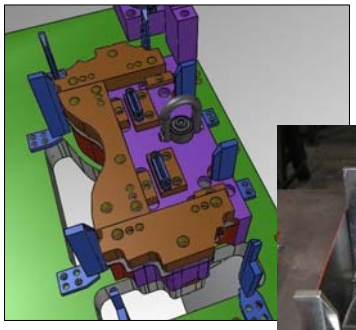
Wrinkle countermeasures required. Due to timing constraints it was decided to incorporate the pad into the design and proceed to tryout.

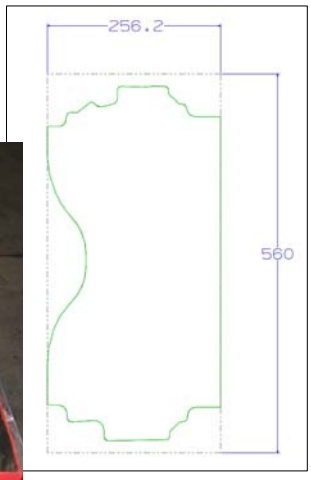
Formability Analysis



STAMPING PROCESS DESIGN

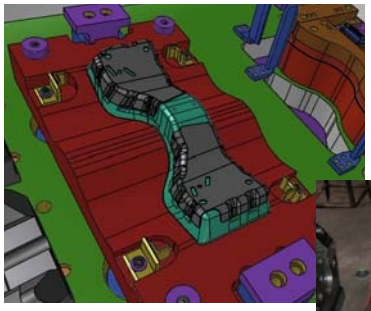
Station #1 Blanking Operation





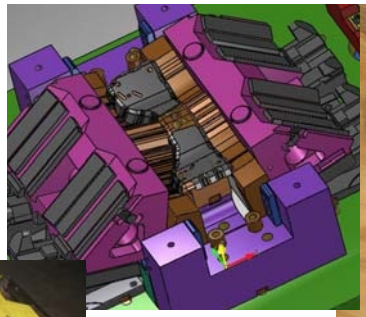
STAMPING PROCESS DESIGN

Station #2 – Draw Die Operation



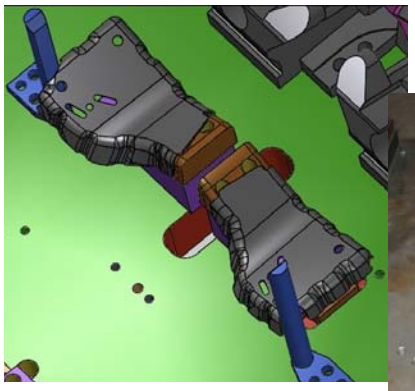
STAMPING PROCESS DESIGN

Station #3 Cam Trim



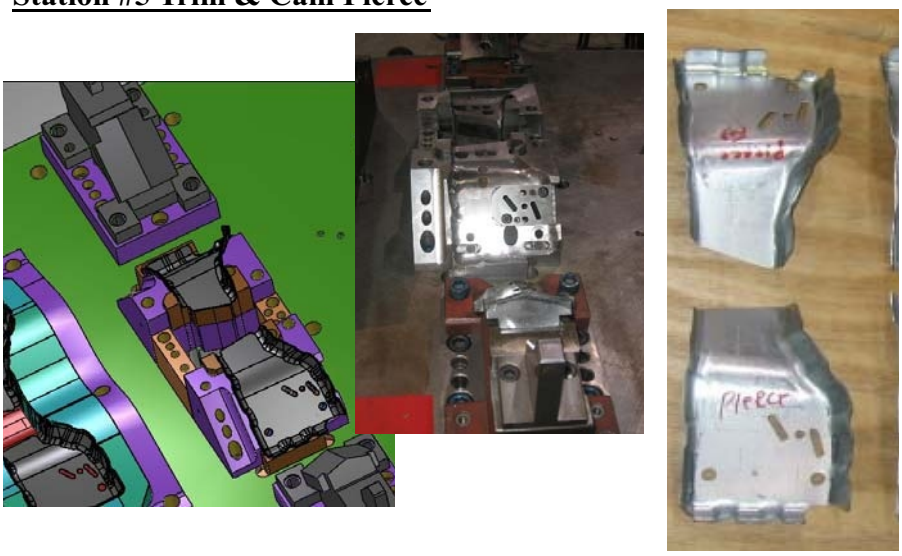
STAMPING PROCESS DESIGN

Station #4 Separate



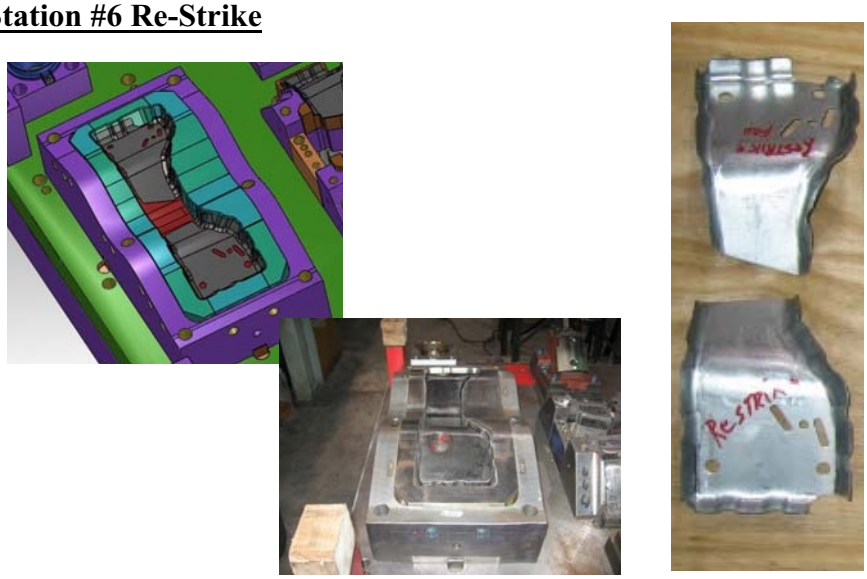
STAMPING PROCESS DESIGN

Station #5 Trim & Cam Pierce



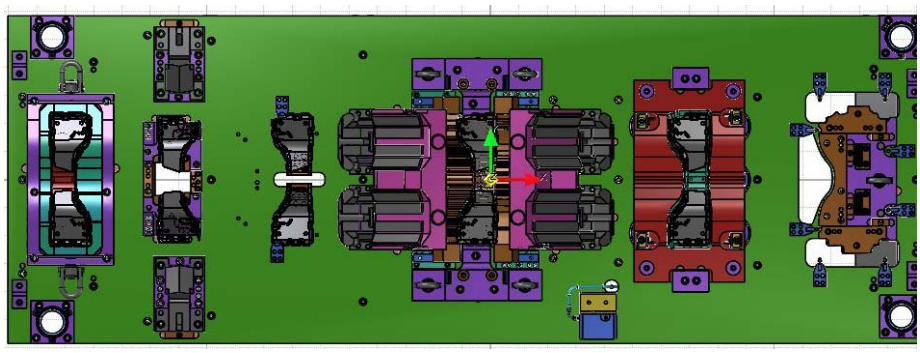
STAMPING PROCESS DESIGN

Station #6 Re-Strike



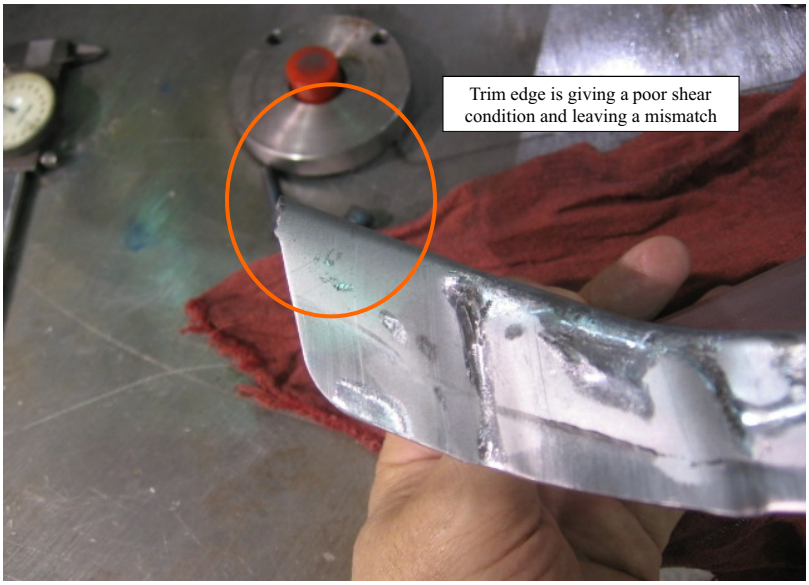
STAMPING PROCESS DESIGN

New Die Design Overview

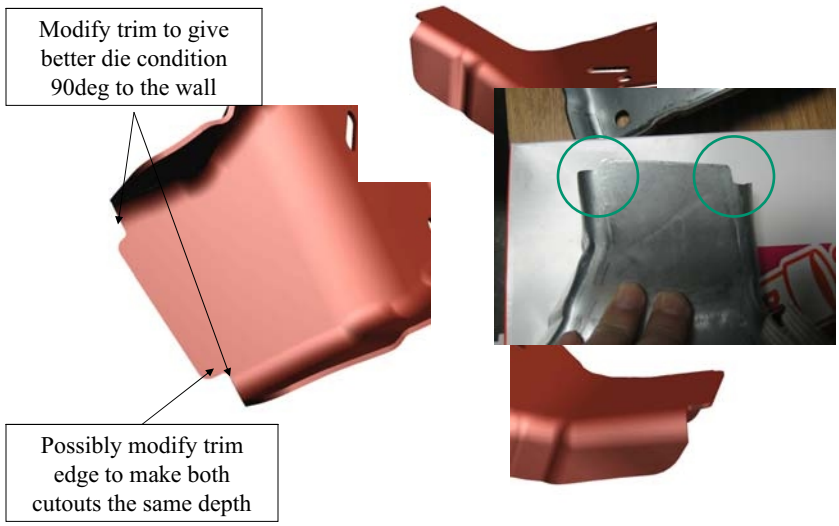


Flow

NEGOTIATED GEOMETRY CONCESSIONS

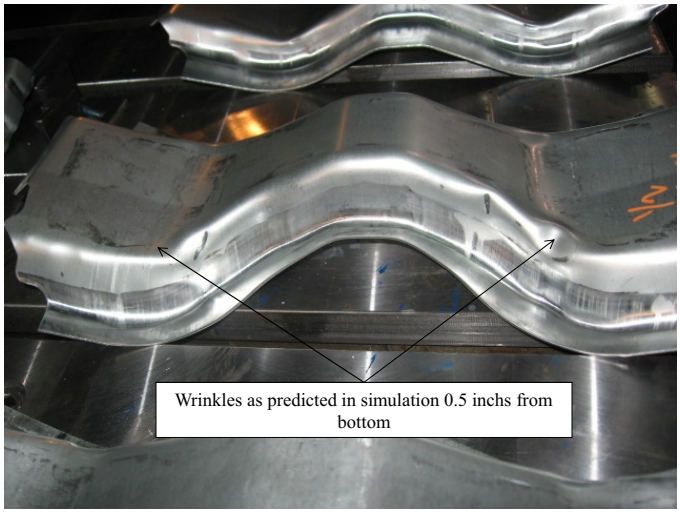


Negotiated Geometry Concessions

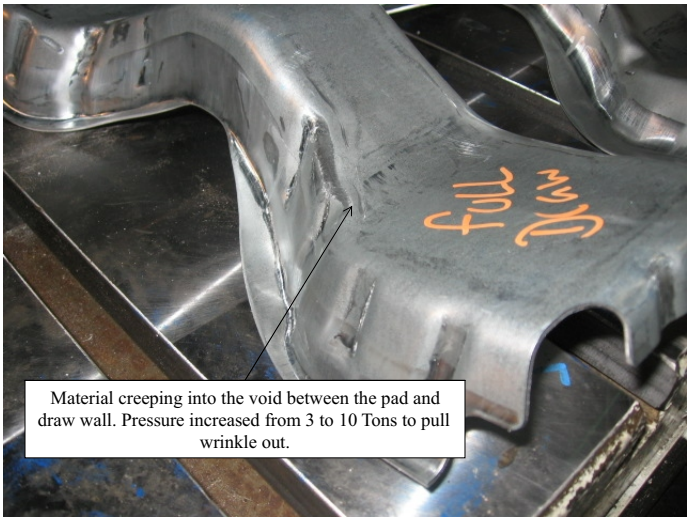


Development Issues

Development Issues

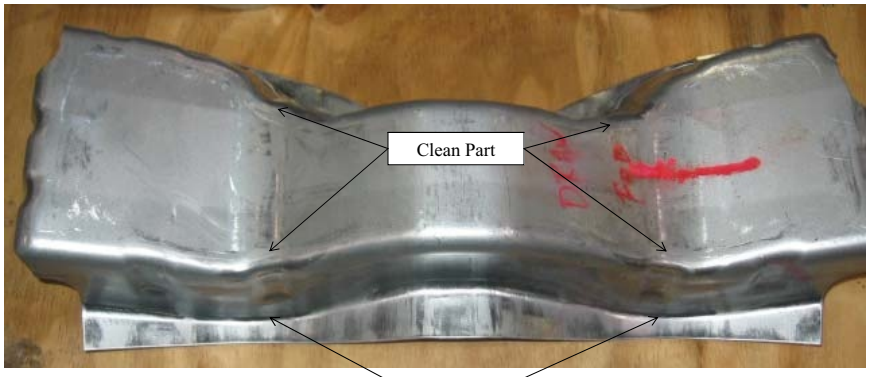


Development Issues



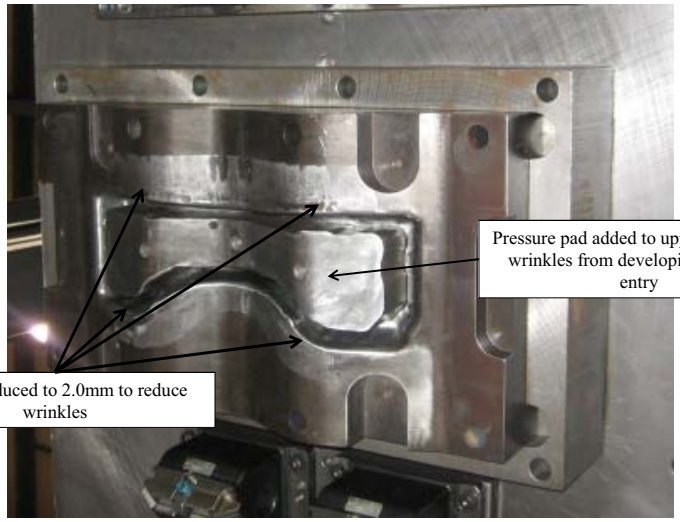
Wrinkle Reduction Countermeasures

Wrinkles shown in simulation reflected actual draw result.
Removed with the countermeasures shown.



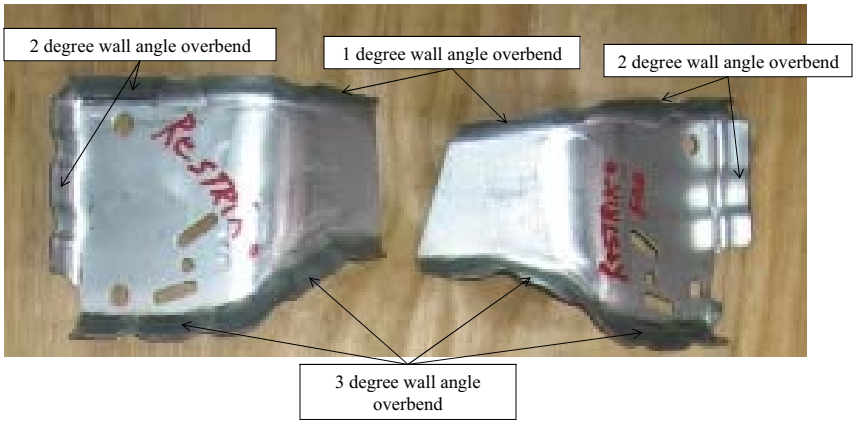
Draw cavity radius was reduced to 2.0mm to effect the removal of the wrinkles.

Wrinkle Reduction Countermeasures



SPRINGBACK COMPENSATION CONTROL HISTORY

Springback compensation was added to all walls of the restrike die prior to cutting based on the development results from laser trimmed drawn parts.



SPRINGBACK COMPENSATION METHODOLOGY

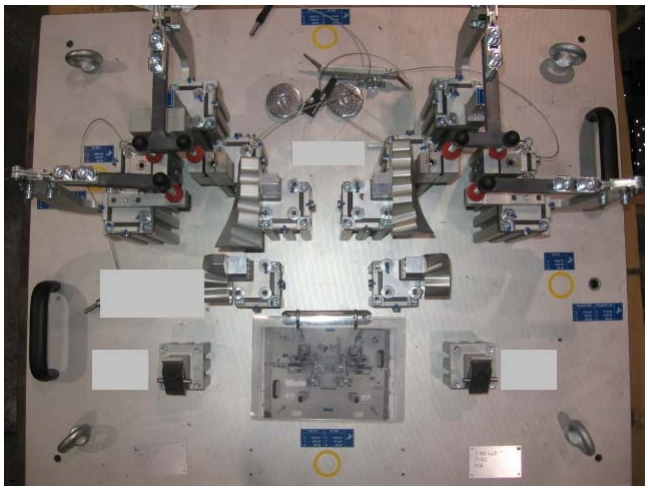
- Developed the draw die using laser cut blanks until functionally acceptable.
- Laser trimmed draw panel to determine springback and required morph of re-strike die.
- Developed re-strike die according to morph.
- No attempt at spring back prediction through software was made due to the lack of useable data for the specified material.
- All estimated compensation angles used were successful after a good spot was attained.
- The draw radius was welded and re-cut three times to reduce the radius and eliminate the wrinkles caused by the binder geometry.
- The best result was achieved at a 2.0mm radius

PRESS LOAD PREDICTION ACCURACY

Die Stage	Press Loads (Tons)				
	Estimate	CAE Prediction	Actual Meas.	Total Available	%
Forming Press	400	300	300	400	75
Binder	20	10	20	30	60
Trimming					
Flange and Pierce					
Restrike					

This material is extremely hard and withstands 10 tons of upper pad pressure without any sign of reversing the part without a lower delay system

Fixturing and Clamping



Fixtures are CMM holding fixture type

LESSONS LEARNED

- Always check the material spec at every change level. The Customer does not always highlight this to the supplier.
- When it comes to these types of complex steels always re-simulate and check your process result before design start.
- Allow for increased tryout time.
- A smaller radius was required to eliminate wrinkling. Only the cavity radii were reduced, the punch radii were unchanged.
- For this particular application, edge stretch forming was extremely limited. Maximum safe elongation was below 10% of the original length of line between two points.
- Try to keep product design for this material to simple geometry without draw. If a draw is absolutely required, then be open to modify the product to improve die conditions and avoid wall angles less than six degrees open.

Section 2

Lessons Learned from Advanced High-Strength Steel Case Studies

Section 2 – Lessons Learned from AHSS Case Studies

AHSS PRODUCT DESIGN GUIDELINES

General Comments

When designing stampings of AHSS, the product designer must make allowances for the characteristics of the material, primarily the increased strength and tendency for springback. As material strength increases, surface transitions must be less abrupt to avoid undesirable results in the finished stamping.

In addition, with increased material strength, some product designs will need to be simplified. This may mean splitting large, complex part designs into smaller, separate stampings. *(See Case Study Summaries #5 & 6)*

Simulation studies of stamping feasibility and springback will prove very useful in designing a practical AHSS product. Modify product design to the simulation data to prevent splits and buckled metal. *(See Case Study Summary #4)* Collaborate with manufacturing engineers to reduce springback issues in the final product design.

Springback

Springback can take several forms such as panel twist, sidewall curl, camber (undercrown /overcrown) and wall or flange springback. This phenomenon is the result of elastic recovery due to residual stresses induced by the stamping process. Residual stress, elastic recovery and the resultant stamping distortions are caused by a combination of material characteristics, the stamping process and part geometry. *(See Figure 2-01 and Case Study Summary #2)*

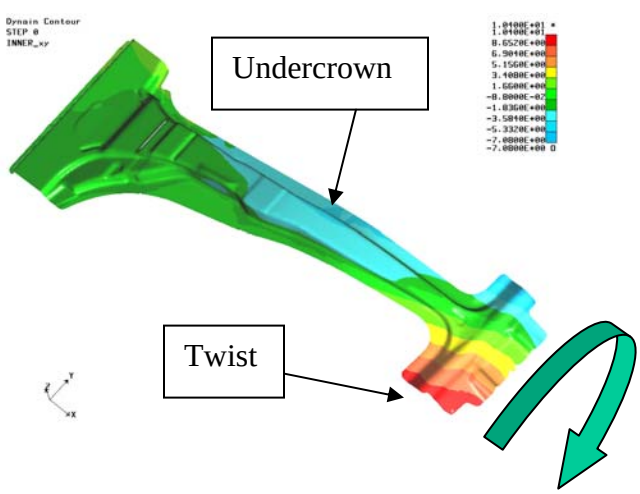


Figure 2.01 Variations of springback

Sidewall angles must be designed more open for springback overbend allowance as material strength increases; at least 6 degrees for DP 600 and 8 degrees for DP 800. 10 degrees or more for DP 1000 is typical. Additional springback allowance may be required in areas of metal compression in sidewalls and flanges. *(See Figs. 2-02, 2-03, 2-06 and Case Study Summary # 7)*

Figure 2.02 DP 600 springback – Part design has 3° open walls.
Die walls are vertical.

Figure 2.03 HSLA springback – Part design has 3° open walls.
Die walls are vertical.

Stretched Edge Cracking

Some AHSS, particularly DP and TRIP grades, have a reduced ability to stretch at the trimmed edge of any stretch flange. Therefore, it is important to minimize these areas by design or to notch the trim edge in these areas whenever possible. Equally important is the need for early steel supplier involvement to discuss the stretch flange requirements in order to select the correct material for the application. If these geometry concessions cannot be accommodated and the part is not limited by drawability, the higher yield ratio AHSS grades with improved edge stretchability, such as complex phase and stretch flangeable grades, can be considered. *(See Figure 2-04 and Case Study Summary #4)*

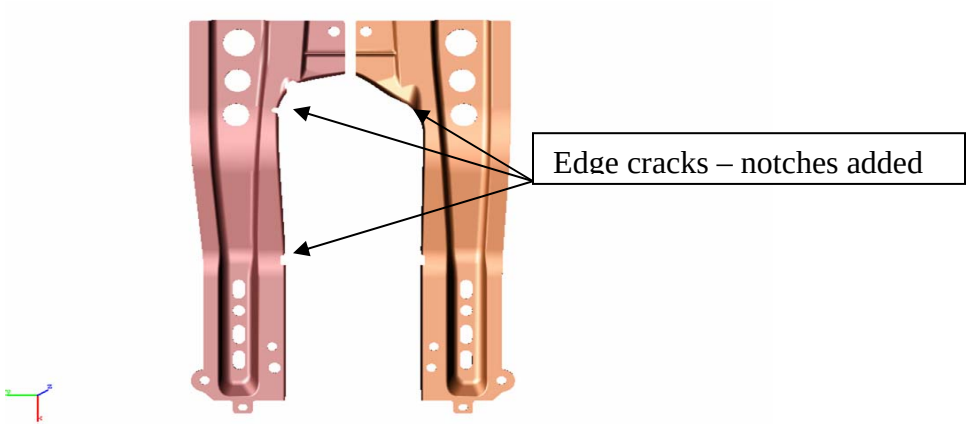


Figure 2.04 Notches for edge cracks at stretch flanges

Part radii must be increased for AHSS. 3 x metal thickness is the minimum for DP 600. This must be increased for higher strength material.

Buckles

Try to equalize depth of the part and length of line in cross sections and lengthwise sections as much as possible. *(See Figure 2-05 and Case Study Summary #2)*

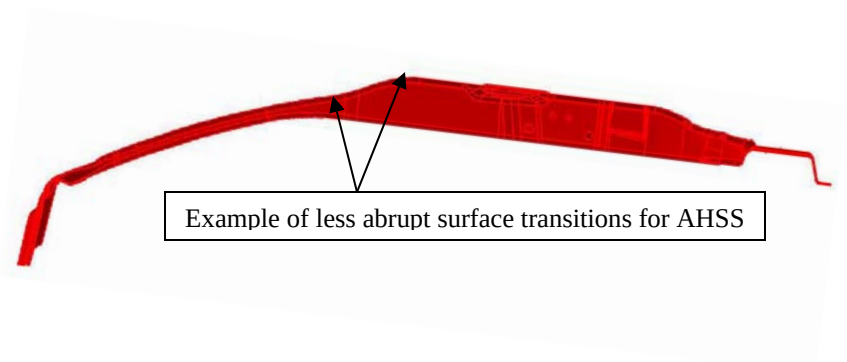


Figure 2.05 Make gradual surface transitions for AHSS

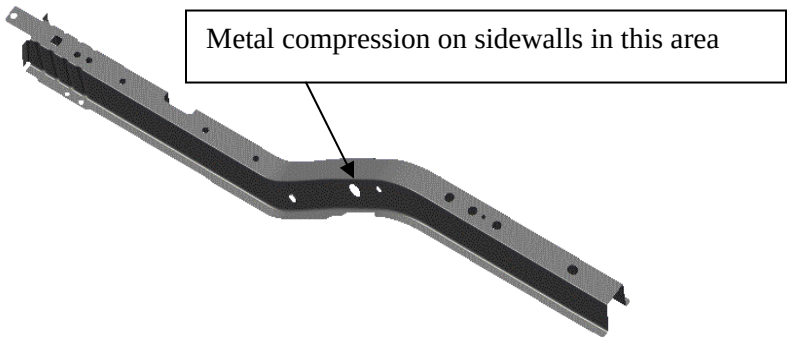


Fig.2.06 Example of Open End AHHS Underbody Rail

Rails, cross bars, pillars, etc. should be designed as open ended channels. *(See Figure 2-06 and Case Study Summary #3)*

AHSS STAMPING PROCESS GUIDELINES

Die Process Planning

- As material strength increases, the stamping process may require modification due to the higher tensile strength and reduced elongation. Forming operations tend to have better results than draw die operations for the higher tensile grades.
- Open end draws or forming operations are required in most cases. Closed end draws must be shallow. *(See Case Study Summary #3)*
- Higher holding pressures will be necessary, both for forming and trimming/piercing. *(See Case Study Summary #1)*
- Higher tool wear rates will require upgraded die materials. *(See Case Study Summary #2)*
- Consider the different die requirements (die materials, lubrication, thermal management, etc.) that are required for tandem press dies, transfer press dies and progressive dies. Higher press speeds and deeper draws will generate more wear and heat. *See Section 2.D. – Summary of Tribology Report.*

Draw and Form Die Recommendations

- A separate press ram is recommended for high tonnage draw and form dies to avoid off-center loads and ram tilting in transfer presses. *(See Case Study Summary #2)*
- Higher binder pressures are required for AHSS stampings. A double action press, hydraulic lead-off press or programmable hydraulic cushion is advantageous. *(See Case Study Summary #1)*
- Morph the first die to FEA springback compensation data. Re-check to a die trimmed panel. *(See Case Study Summary #2)*
- Heat issues may be a problem in the higher speed/deeper draw operations. Use draw lube or die cooling as necessary.
- Form as much of the finish shape as possible in the first die. Do not rely on a re-strike die to correct major shape problems. *(See Case Study Summary #1)*
- Try to get all stretch flanges to finish position before trimming. *(See Case Study Summary #2)*
- Use hard weld on all draw beads and any high wear die radius. These areas must be polished to avoid stripping off sheet steel coatings, particularly Galvanneal.
- Utilize more "robust" die construction standards and materials to reduce die wear and flexing. *(See Case Study Summary #7)*

- Pocket or key all flange steels. Do not rely on dowels to contain thrust. *(See Case Study Summary #2)*Bottom all form die pads. Coin all flange radii to reduce springback. *(See Case Study Summary #2)*
- Cam drivers should be heeled for heavier work loads.
- Product feature radii typically > 3 x T for DP 600.
- Die radii typically > 5 x T for DP 600.
- Use white light scanning or hard fixture for springback evaluation and compensation during die tryout.

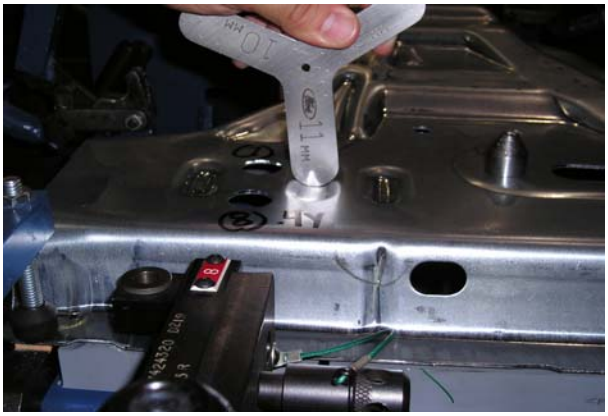
Blanking, Trimming, Piercing Recommendations

- Trim die "snap through" from AHSS can cause die and press damage. Provide shear and some method of absorbing this shock as needed.
- Trim and pierce angles should be 10 degrees or less. No acute angles. *(See Case Study #2)*
- Upgrade to better trim die materials such as D2 or S-7.
- Piercing angle should be 90 degrees to surface for small diameter punches.
- Pierce punch and button materials should be upgraded for AHSS applications.

Re-Strike Dies

Do not rely on re-strike die to correct over/under crown or twist. (See Fig. 2-01)

Fig. 2.07 Depressions added by re-strike die to correct wrinkled surface metal



Figs. 2.08 Darts and beads added by re-strike die for springback control

- Re-strike die can add darts, stiffening beads, etc. These features, added by the re-strike die, can be used to correct wrinkles and springback in some cases. *(See Fig.2-07, 2-08 and Case Study summary #2)*

Countermeasures for Springback Control

- Build first draw / form die to simulation studies for forming limits and springback data.
- Further revision of the first die may be necessary after comparing a die trimmed stamping to product design data either by scanning or with a hard fixture.
- Twist and camber problems should be resolved in the first die operation. Springback problems of this type are often aggravated by the following trim and flange die operations. *(See Case Study Summary #5)*
- Set-up part in die to allow proper overbend for springback. 6 degrees or more for DP 600.
- Get as much finish shape in the first stamping as possible.
- Increased binder pressure can reduce springback in many cases. (See Case Study Summary #2)
- Stretching the stamping sidewalls will reduce sidewall curl.
- Forming operations typically produce less sidewall curl than draw dies.
- Coin all flange breaks in form and flange dies to reduce springback.
- Bottom all form die pads. *(See Case Study Summary #5)*
- Try not to re-form work hardened areas of the stamping.
- Re-strike dies can be used to coin some radii or add darts and beads for springback control.
- Build robust dies that will prevent flexing due to offset loading or flanging thrust.
- Back up all flanging steels with keys or a solid die member. Do not rely on dowels.
- Provide adequately sized heels and/or guide pins to prevent die shift.

- Balance all offset die and press loads. When possible, use a separate press slide for large, offset draw or form die loads. *(See Case Study Summary #2)*

Piercing Recommendations for AHSS

Piercing tools (punches, buttons and retainers) for AHSS should be selected with consideration given to strength, toughness and wear requirements for the sheet steel material specified. Materials typically used for these AHSS applications are D2, S7, M4, or specialty steel products like Vanadis4®.

Punch specifications

- Consider the sheet steel material thickness, strength and the length or circumference of holes to be pierced. Calculate the compressive load on the punch. If the compressive load exceeds 60% of the rated value of a given tool steel, random punch failures will occur. At 100% of the rated value, failure is a probability.
- Only heavy duty punches with material upgrades should be specified.
- Proper punch material, shank size, length and shoulder radius are critical.

Punch Retainer specifications

- Heavy duty punch retainers with hardened backing plates (48 – 52 HRC) must be specified to avoid failures in the retention ball and screws. Repeated compression, press "snap through" and stripping cycles will eventually cause failure of undersized retainers and internal components.

Pierce buttons and lower steels

- A die clearance of 10 – 15% is recommended.
- Avoid any acute corners in the cutting edge of lower steels and buttons.
- Avoid severe relief undercuts below the button cutting edge.
- Calculate load force to determine button size and material. (same as for punch)
- Do not exceed 60% of rated load value of the button material selected.
- Support die buttons with hardened slug-breaker plates.
- Button material must also be upgraded for toughness and compressive strength.

Punch Coatings

- Punch surface coatings are recommended for working the thicker, higher strength grades, particularly in high-speed press applications.
- PVD or CVD coatings containing nitrides or carbides are recommended for more severe applications.

Piercing Angles

- Piercing of small diameter holes, less than 6mm, should be square to surface only. For holes larger than 6mm, piercing angles should be kept to a minimum with consideration given to material strength and thickness.

Summary of A/SP Tribology Group Die Wear Test (Phase 1)

The Tribology Group of the Auto/Steel Partnership is conducting research on the effects of AHSS on stamping die wear to determine the optimum materials and die conditions for improving tooling performance. A variety of die materials, coatings and trim conditions are included in this research. Die tooling materials and coatings are being ranked in order of performance. Phase 1 tests are being conducted with DP980 uncoated as the sheet stock. Future tests (Phase II) are planned with DP 980 GA and TRIP 780 GA and uncoated, using the lessons learned from Phase 1.

Phase 1 Test

- DP 980 uncoated in a progressive form, flange, trim and pierce test die. The tests were extended to 60,000 hits.

Trim Steel Conclusions

- Trim steel material selection is critical.
- Material ranking: D2 > S7 > M4 > CPM10® > Caldie™ > CC1®> Vanadis 4®.
- Trim steel hardness significantly improves performance.
- Acute trim angles result in accelerated die wear and chipping.
- 90 degree trim angles will minimize wear and chipping.

Flange Steel Conclusions

- Hardness has little impact on performance.
- Surface coating has major impact on performance and durability.
- Material ranking: D2+CVD TiC > Carmo™+N+PVD (IonBond) >> D2+AiTiN > Carmo™+CrN (Phygen-Fortiphy®) > M2+PVD CrN >> Vanadis 4®=M2=M4 > D2.

Piercing Steel Conclusions

- Burr height increases with die clearance. 10–15% die clearance is acceptable.

Forming Steel Conclusions

- Forming steels show least wear. Bare D2, Cr, TD and CVD TiC were all in good condition after 60,000 hits.

Temperature

- Temperature increased most on uncoated flange steels. Bare D2 insert temperature rose to 170° F. Part Temperature at 130°F.

Added Note: Completion of Phase 1 tests will add heels and ball bearing guide pins to the progressive die. Improved die structure for die alignment and thrust control should extend life of tool steels, particularly for trim and pierce operations.

Additional information on the Tribology Group Die Wear Test will be available online at: www.a-sp.org.

Section 3

Glossary

Glossary – AHSS Applications Guidelines

AHSS (Advanced High-Strength Steel): A series of high-strength steels containing microstructural phases other than ferrite and pearlite. These other phases include martensite, bainite, retained austenite, and/or austenite in quantities sufficient to produce unique mechanical properties. Most AHSS have a multi-phase microstructure.

AKDQ (Aluminum-Killed Draw-Quality steel): A highly formable grade of mild steel that is usually aluminum deoxidized and commonly used around the world for a large number of sheet metal stampings. See Mild Steel.

Angular change: Springback resulting from a change in sheet metal curvature at the punch radius. The springback angle describes the resulting change in flange position.

Anisotropy: Variations in one or more physical or mechanical properties with direction.

> **Normal anisotropy –** A condition where a property in the sheet thickness direction differs in magnitude from the same property in the plane of the sheet. The common measurement is r_m or the mean r-value of plastic strain ratios taken at 0°, 45°, 90°, and 135° to the coil rolling direction.
>
> **Planar anisotropy –** A condition where a property varies with direction in the plane of the sheet. The planar variation in plastic strain ratio (Δr) indicates the tendency of the sheet metal to ear during deep drawing.
>
> **Plastic strain ratio –** A measure of plastic anisotropy (r) defined by the ratio of the true width strain to the true thickness strain in a tensile test.

Austenite: A face-centered cubic crystalline phase, also known as gamma (**γ).** At room temperature, it is a feebly magnetic homogenous phase consisting of a solid solution of no more than 2% carbon and significant amounts of manganese and/or nickel. It has an inherently high n-value and high elongation, therefore providing improved formability over other crystalline structures of comparable strength. It is the primary phase of steel at elevated temperatures after solidification prior to cooling, but is not present in conventional steels at room temperature. With proper alloying, high temperature austenite can be rapidly quenched to produce martensite.

> **Retained austenite -** Austenite present in the microstructure at room temperature resulting from proper chemistry and heat-treating. With sufficient subsequent cold work, this retained austenite can transform into martensite.

Bainite: A mixture of α-iron and very fine carbides that has a needle-like structure and is produced by transformation of austenite. Replacing the ferrite with bainite helps strengthen the steel.

Bake hardening index: The change in yield strength created in a tensile test sample given a 2% stretch and then followed by a typical automotive paint bake cycle.

BH (Bake Hardening steel): A low carbon, cold formable sheet steel that achieves an increase in strength after forming due to a combination of straining and age hardening. Increasing the temperature accelerates the aging-hardening process.

Batch (box) annealed steel: A large stationary mass of cold worked steel coils heated and slowly cooled within the surrounding furnace to return the steel microstructure to a more formable condition and desired size of undeformed grains.

Binder: The upper and lower holding surfaces that control sheet metal flow into the draw die cavity and prevent wrinkling. Often, the terms blankholder or holddown are used.

Blank: A pre-cut sheet metal shape ready for a stamping press operation.

> **Developed blank -** A flat sheet steel blank with a profile that produces a finished part with a minimum of trimming operations. Blank cutting dies produce this type of blank for form dies.
>
> **Rough blank -** A flat sheet steel blank with a rectangular, trapezoidal, or chevron periphery. Shear lines or cutoff dies produce these blanks for draw die or stretch-form die applications.

Blankholder: The part of the draw die's binder that has pressure adjustment. Other names are binder or holddown.

> **Programmable blankholder -** A blankholder actuated by a press or die cushion programmed to vary the pressure profile during the draw die process. AHSS stampings can often benefit from a variable cushion pressure profile during the press stroke.

Burr: The rough, sharp protrusion above the surface of a stamped, pierced, or slit edge of metal which is exacerbated by worn trim steels or improper die or knife clearance. Although unavoidable in metal cutting except with fine blanking, it should be minimized due to problems it causes with edge stretching & forming, handling, and contact issues.

Carbide (Iron Carbide): A hard iron-carbon phase (FE_3C) that is formed during solidification (primary carbides) or during cooling (cementite).

Carbon Equivalent: The amount of carbon, manganese, chromium, molybdenum, nitrogen and other elements that have the same effect on a steel's weldability as a steel containing carbon without these elements using various carbon equivalent prediction formulas.

CM (Carbon Manganese steel): High-strength steels with strength increased primarily by solid solution strengthening.

Clinching: Mechanical joining operation where the punch forces two sheets of metal to spread outward in the die and interlock.

CP (Complex Phase steel): Steel with a very fine microstructure of ferrite and higher volume fractions of hard phases and further strengthened by fine precipitates.

Computerized forming simulation: More accurately titled as computerized forming-process development, computerized die tryout, or virtual sheet metal forming. Forming the virtual stamping in the computer provides validation of product, process, and die design information before beginning construction of hard tooling. Applications include determination whether the initial product design can be formed, evaluation of various product and process design options, and acquisition of additional production requirements, such as maximum required press load and blank size/shape.

Continuous annealed steel: Steel that is unwrapped as it is pulled through a long continuous furnace and then through a cooling or quench region to recrystallize the microstructure and obtain the desired physical properties. The alternative annealing method is batch annealing. Also can be used for transformation strengthening (martensite formation).

Cup drawing: A press forming operation in which a sheet metal blank (usually circular) forms a cup shaped part (often cylindrical).

Curl (sidewall): Springback resulting from metal bending and unbending over a radius and/or drawbead. Curl is characterized by an average radius of curvature.

Die clearance: The gap or distance between the die surfaces as the press is in operation.

Double action press: A press with inner and outer slides to activate draw dies. Usually, the outer slide drives the blankholder and the inner slide drives the punch.

Draw bead: A small ridge of metal on the blankholder to restrain the flow of sheet steel into the die cavity.

> **Active draw bead -** Draw beads that are separate from the binder. They are usually below the surface of the binder at the beginning of the press stroke and are mechanically lifted near the bottom of the press stroke to increase restraint of the sheet metal flow off the binder.
>
> **Square lock bead -** A small, square-shaped ridge of metal on the blankholder to prevent metal flow off the binder in stretch-form dies.

Draw development: The process of developing a die-setup for the stamping (including the flange trim angles, addendum sheet metal, and binder surfaces) to design a draw die and subsequent trim die operation.

Draw die: A die in which sheet metal circumferentially compresses (minor axis) on the binder and radially elongates (major axis) when pulled off the binder and into the die cavity by the punch. Most automotive body draw die stampings will have circumferential compression located primarily in the corners of the stamping. Draw stampings for parts such as cups and cans will have circumferential compression around the entire punch line. Automotive body panel draw die processes normally require a rough blank, draw beads on the binder, and subsequent trim die operations to remove the binder offal. The term is also used colloquially to identify the first die in a multiple stage forming process used to produce a stamped part.

> **Cushion draw die -** A draw operation performed in a single-action press with blankholder force supplied by an air, nitrogen, or hydraulic pressure cushion.
>
> **Double action draw die -** A draw die actuated by a double action press that has separate slides to drive the die punch and blankholder.

DQSK (Draw-Quality Special-Killed steel): A highly formable grade of mild steel that is usually aluminum deoxidized. Also called Aluminum-Killed Draw-Quality (AKDQ) steel. See Mild Steel.

DP (Dual Phase steel): Steel consisting of a ferrite matrix containing a hard second phase, usually islands of martensite.

Elastic deformation: Deformation that will return to its original shape and dimensions upon removal of the load or stress.

Elastic limit: The maximum stress to which a material may be subjected and yet return to its original shape and dimensions upon removal of the stress.

Elastic recovery: The reaction of sheet metal to the release of elastic and residual stresses. The reaction increases as the strength of the steel increases.

Elongation: The amount of permanent plastic deformation in a tensile test or any segment of a sheet metal stamping.

> **Local elongation:** The percent of permanent stretch deformation in a localized area over a very short gauge length. It is highly affected by the material microstructure. Local elongation is commonly measured by a conical hole expansion test and expressed as a percentage increase (**λ**) in hole diameter.
>
> **Total elongation -** A measure of ductility obtained from a tensile test. Values are the final gage length minus original gage length divided by the original gage length and then changed to percent. Different regions of the world use different gauge lengths and specimen widths.
>
> **Uniform elongation -** A measure of ductility obtained from a tensile test. Values are the gage length at maximum load (UTS) minus original gage length divided by the original gage length and then changed to percent.

Embossing: Forming or displacing a section of metal without metal flow from surrounding sheet metal.

Engineering strain: The percent unit elongation obtained by the change in length divided by the original length.

Engineering stress: The unit force obtained when dividing the applied load by the original cross-sectional area.

Erichsen test: A spherical punch test that deforms a piece of sheet metal, restrained except at the centre, until fracture occurs. The height of the cup at fracture is a measure of ductility. This test is similar to the Olsen test.

Ferrite (α): A body-centered cubic crystalline phase of steel. It is the microstructure of pure iron, and can have this lattice structure with up to .022%% carbon in solid solution.

FB (Ferritic-Bainitic steel): Steel with a microstructure containing ferrite and bainite. The bainite provides strength and replaces the islands of martensite in DP and TRIP steels to provide improved edge stretchability.

Filler metal: Metal added during arc welding that is available in the form of rods, spooled wire, or consumable inserts.

Form die: A die process capable of producing part surface contours as well as peripheral flanges. Usually, a developed blank is used which reduces or eliminates the need for subsequent trim die operations.

> **Draw-action form die -** A form die in which an external pressure pad (similar to a binder) controls compression and buckles on flanges during the deformation process. This type of die normally utilizes a developed blank, which eliminates the need for a following trim die operation. Draw beads are not used.
>
> **Open-end form die -** A die process similar to a draw die, but with little or no compression of the sheet metal due to the absence of closed corners at the ends of the stamping. A rough blank is used and a subsequent trim die operation is necessary, similar to that required for the draw die process. Draw beads often are used. Rails and channel shaped parts frequently are stamped this way.
>
> **Post-stretch form die -** A form die with the sheet metal stamping locked out and stretched over the post or punch shortly before the press reaches bottom dead centre. This post-stretch reduces residual stresses that cause springback and other distortions in HSS stampings.
>
> **Stretch-form die -** A die similar to a draw die with the sheet metal restrained by lock beads on the binder surface. A rough blank is used. The sheet undergoes biaxial stretch to form the part. Subsequent trim die operations are required to remove the lock beads.

FLC (Forming Limit Curve): An empirical curve showing the different combinations of biaxial strain levels beyond which failure (local necking) may occur in sheet metal forming. The strains are given in terms of major and minor strains measured from ellipses previously imprinted as circles on the undeformed sheet metal.

GMAW (Gas Metal Arc Welding): An arc welding process that uses a continuously fed consumable electrode and a shielding gas. Common GMAW processes are MIG (metal inert gas) welding and MAG (metal active gas) welding.

HAZ (Heat Affected Zone): The zone adjacent to the weld fusion zone where heat generated by the welding process changes base metal properties and grain size.

Heat balance: The phenomenon in resistance spot welding of balancing the heat input during the weld based on the gauge and grade of steel.

HHE (High Hole Expansion steel): A specific customer application requirement to improve local elongation for hole expansion and stretch flanging operations. A variety of special steel types may meet these specific specifications.

HSLA (High-Strength, Low-Alloy steel): Steels that generally contain microalloying elements such as titanium, vanadium, or niobium to increase strength by grain size control, precipitation hardening, and solid solution hardening.

HSS (High-Strength steel): Any steel product with initial yield strength greater than 210 MPa or a tensile strength greater than 270 MPa.

HET (Hole expansion test): A formability test in which a tapered (usually conical) punch is forced through a punched or drilled and reamed hole forcing the metal in the periphery of the hole to expand in a stretching mode until fracture occurs.

HF (Hot-Formed steel): A quenchable steel that is heated to transform the microstructure to austenite and then immediately hot-formed and in-die quenched. Final microstructure is martensite. HF steel provides a combination of good formability, high tensile strength, and no springback issues. Most common HF steels are boron based.

Hybrid joining: Combining adhesive bonding with resistance spot welding, clinching or self-piercing rivets to increase joint strength.

IF (Interstitial-Free steel): Steel produced with very low amounts of interstitial elements (primarily carbon and nitrogen) with small amounts of titanium or niobium added to tie up the remaining interstitial atoms. Without free interstitial elements, these steels are very ductile and soft, will not age or bake harden, and will not form strain (Lüder's) lines during forming due to the absence of YPE (yield point elongation).

IS (Isotropic steel): A ferritic type of microstructure modified so the Δr value is approximately zero to minimize any earing tendencies.

K-value: Determined from the plot of log true stress versus log true strain, K is the value of true stress at a true strain of 1.0. The K-value is an important term in the power law equation $\sigma = K\epsilon^n$.

ksi: An English unit of measure for thousands of pounds per square inch. One ksi = 6.895 MPa. MPa and ksi are units of measure for stress in materials and pressure in fluids.

Limiting Draw Ratio (LDR): An expression of drawability given by the highest drawing ratio (blank diameter divided by punch diameter) without cup failure. The Swift cup test often is the required series of tests utilized to measure the LDR.

Major strain: Largest positive strain at a given point in the sheet surface measured from a circle grid. The major strain is the longest axis of the ellipse. The press shop term often is major stretch.

MS (Martensitic steel): A body-centered tetragonal crystalline phase of steel. It is the primary strengthening phase in Dual Phase steels and Martensitic steels are 100% martensite. It is a hard phase that can form during the quenching of steels with sufficient carbon equivalents. Martensite can also be formed by the work hardening of austenite.

MPa (Mega Pascal): A metric measure of stress in materials and pressure in fluids. One MPa = 0.145 ksi.

MAG (**Metal Active Gas):** See Gas Metal Arc Welding (GMAW).

Metal gainer: A preformed area of the stamping that temporarily stores surplus material which is subsequently used to feed metal into an area that normally would be highly stretched and torn. Alternatively, the term is used to describe a post-forming operation where surplus material is permanently stored in stamped shapes to prevent buckles.

MIG (Metal Inert Gas): - See Gas Metal Arc Welding (GMAW).

Microstructure: The contrast observed under a microscope when a flat ground surface is highly polished, and then thermally or chemically etched. The contrast results from the presence of grain boundaries and different phases, all of which respond differently to the etchant. A photomicrograph is a picture of the resulting microstructure.

MFDC (Mid-Frequency Direct Current): MFDC has the advantage of both unidirectional and continuous current.

Mild steel: Low strength steels with essentially a ferritic microstructure and some strengthening techniques. Drawing Quality (DQ) and Aluminum-Killed Draw-Quality (AKDQ) steels are examples and often serve as a reference base because of their widespread application and production volume. Other specifications use Drawing Steel (DS), Forming Steel (FS), and similar terms.

Minor strain: The least strain at a given point in the sheet surface and always perpendicular to the major strain. In a circle grid, the minor strain is the shortest axis of the ellipse. The press shop term often is minor stretch.

MP (Multi-phase steel): See AHSS (Advanced High Strength Steels).

Multiple stage forming: Forming a stamping in more than one die or one operation. Secondary forming stages can be redraw, ironing, restrike, flanging, trimming, hole expansion, and many other operations.

n-value: The work hardening exponent derived from the relationship between true stress and true strain. The n-value is a measure of stretchability. See work hardening exponent.

> **Instantaneous n-value -** The n-value at any specific value of strain. For some AHSS and other steels, the n-value changes with strain. For these steels, a plot of log true stress versus log true strain allows measurement of the slope of the curve at each point of strain. These slope measurements provide the n-value as a function of strain.
>
> **Terminal n-value -** The n-value at the end of uniform elongation, which is a parameter influencing the height of the forming limit curve. In the absence of an instantaneous n-value curve, the n-value between 10% elongation and ultimate tensile strength (maximum load) from a tensile test can be used as a good estimate of terminal n-value.

Necking: A highly localized reduction in one or more dimensions in a tensile test or stamping.

> **Diffuse necking -** A localized width neck occurring in tensile test specimens that creates the maximum load identified as the ultimate tensile strength (UTS).
>
> **Local necking -** A through-thickness neck that defines the forming limit curve and termination of useful forming in the remainder of the stamping. No deformation takes place along the neck. Further deformation within the local neck leads to rapid ductile fracture.

Overbend: Increasing the angle of bend beyond the part requirement in a forming process to compensate for springback.

Over/Undercrown: A type of springback affecting the longitudinal camber of stampings such as rails and beams.

Pearlite: A lamellar mixture or combination of ferrite and carbide.

Plastic deformation: The permanent deformation of a material caused by straining (stretch, draw, bend, coin, etc.) past its elastic limit.

Post-annealing: An annealing cycle given to a stamping or portion of the stamping to recrystallize the microstructure and improve the properties for additional forming operations or in-service requirements.

PFHT (Post-Formed Heat-Treatable steel): Heating and quenching formed stampings off-line in fixtures to obtain higher strengths. A broad category of steels having various chemistries is applicable for this process.

Post-stretch: A stretch process added near the end of the forming stroke to reduce sidewall curl and/or angular change resulting from the stamping process. Active lock beads, lock steps, or other blank locking methods prevent metal flow from the binder to generate a minimum of 2% additional sidewall stretch at the end of the press stroke.

Process capability: The variation of key dimensions of parts produced from a die process compared to the part tolerances.

Process variation: Two components make up process variation. One is the variation caused by differences in run-to-run press and die setups. The second is the part-to-part variation within the same run caused by process variables such as lubrication, cushion pressures, die temperatures, non-uniform material, etc.

Punchline: The line between the draw die binder and the draw die punch in the plan view of the die drawing.

Quasi-static: Traditionally the strain rate during a tensile test, which is very slow compared to deformation rates during sheet metal forming or a crash event.

Residual stresses: Elastic stresses that remain in the stamping upon removal of the forming load. Residual stresses are trapped stresses because the final geometry of the stamping does not allow complete release of all elastic stresses.

Restrike die: A secondary forming operation designed to improve part dimensional control by sharpening radii, correcting springback, or incorporation of other process features.

Sheared edge stretchability: Reduced residual stretchability of as-sheared edges due to the high concentration of cold work, work hardening, crack initiators, and pre-cracking at the sheared interface.

Shrink flanging: A bending operation in which a narrow strip at the edge of a sheet is bent down (or up) along a curved line that creates shrinking (compression) along the length of the flange.

Sidewall curl: Springback resulting from metal moving over a radius or through draw beads. Curl is characterized by an average radius of curvature.

Simulative formability tests: These tests provide very specific formability information that is significantly dependent on deformation mode, tooling geometry, lubrication conditions, and material behavior. Examples include hemispherical dome tests, cup tests, flanging tests, and other focused areas of formability.

Single action press: A press with a single slide to activate the die.

Springback: The extent to which metal in the stamping deviates from the designed or intended shape after undergoing a forming operation. Also the angular amount a metal returns toward its former position after being bent a specified amount.

Strain gradient: A change in strain along a line in a stamping. Some changes can be very severe and highly localized and will have an accompanying increase in thickness strain.

Strain rate: The amount of strain per unit of time. Used in this document to define deformation rate in tensile tests, forming operations, and crash events.

SF (Stretch Flangeable steel): A specific customer application requirement to improve local elongation for hole expansion and stretch flanging operations. A variety of special steel types may meet these specific specifications.

Stretch flanging: A bending operation in which a narrow strip at the edge of a sheet is bent down (or up) along a curved line that creates stretching (tension) along the length of the flange.

Tempering pulse: A post-weld heat treatment or post-annealing to improve the weld fracture mode and the weld current range.

TS (Tensile Strength): Also called the ultimate tensile strength (UTS). In a tensile test, the tensile strength is the maximum load divided by the original cross-sectional area.

TRIP (Transformation-Induced Plasticity steel): A steel with a microstructure of retained austenite embedded in a primary matrix of ferrite. In addition, hard phases of martensite and bainite are present in varying amounts. The retained austenite progressively transforms to martensite with increasing strain.

True strain: The unit elongation given by the change in length divided by the instantaneous gage length.

True stress: The unit force obtained from the applied load divided by the instantaneous cross-sectional area.

TWIP (Twinning-Induced Plasticity steel): A high manganese steel that is austenitic at all temperatures – especially room temperature. The twinning mode of deformation creates a very high n-value, a tensile strength in excess of 900 MPa, and a total elongation in excess of 40%.

Twist: Twist in a channel defined as two cross-sections rotating differently along their axis.

UTS (Ultimate Tensile Strength): See Tensile Strength.

UFG (Ultra fine grain steel): Hot-rolled, higher strength steel designed to avoid low values of blanked edge stretchability by replacing islands of martensite with an ultra-fine grain size. An array of very fine particles can provide additional strength without reduction of edge stretchability.

ULSAB-AVC (UltraLight Steel Auto Body – Advanced Vehicle Concepts): Information is available at www.worldautosteel.org.

ULSAC (UltraLight Steel Auto Closures): Information is available at www.worldautosteel.org.

Work hardening exponent: The exponent in the relationship $\sigma = K\epsilon^n$ where σ is the true stress, K is a constant, and ϵ is the true strain. See n-value.

YS (Yield Strength): The stress at which steel exhibits a specified deviation (usually 0.2% offset) from the proportionality of stress to strain and signals the onset of plastic deformation.

Section 4

Die Sketches

Die Sketches

The following die sketches are very simplified versions of some of the stamping processes that have been used by the Auto/Steel Partnership's AHSS Stamping Group in determining the effectiveness of various processes for the production of AHSS automotive structural components. Most of these processes are forming operations or some type of cross-over process between forming, stretching and/or drawing. Nomenclature for these processes is often arbitrary and varies within different companies.

The following observations have been made by the A/SP AHSS Stamping Group during these studies:

- Processes that produce elongation in the stamping (such as draw dies) will provide the most tensile strength increase in Dual Phase stampings. See figures 4.04 and 4.09.

- Draw die developments must consider and compensate for the elastic recovery of the stamping after the binder scrap has been removed by the trim die operations. See figures 4.09.

- Form die processes produce less residual stress in the stamping than draw die processes and generally work well for AHSS if the part geometry is not overly complex. See figures 4.01 and 4.07.

- AHSS has an increased tendency to buckle during deformation as opposed to the draw quality steel grades. This characteristic must be controlled by various process adjustments such as higher holding pressures, double pad processes and die material upgrades. See figures 4.05 and 4.09.

- Trim edge cracking has also been a problem. This issue can be alleviated by the proper material selection for the part and process. Discuss this with your steel company representative early on. A process to draw in the trim edge may also be required. See figure 4.09.

- Sidewall curl is worse with lower pad operations (see figure 4.07) than upper pad operations (see figure 4.01) due to the sheet steel tightly wrapping the upper flange steel radius during the lower pad forming process.

- These basic sketches may not illustrate some important criteria for AHSS die operations:
  - All pads and binders should bottom.
  - Flange steels should coin the flange radius.
  - Proper die clearance is critical.
  - Higher binder pressures and restraining forces are necessary.
  - Upgraded die materials are required.
  - A more robust die construction is also required.

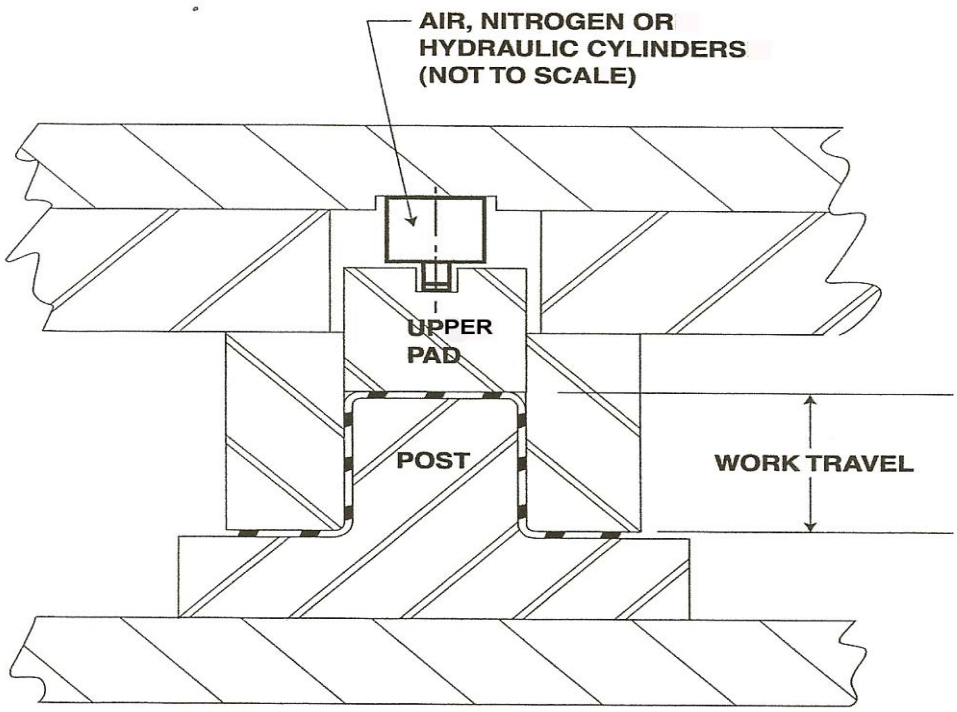


Figure 4.01 – Form Die (Upper Pad)

Form dies for AHSS parts with mild contours in the die plan view or elevation will require an upper pressure pad. . Pressure pad must "bottom out" at the bottom of the press stroke. Part contours must be mild enough for minimal metal compression (no buckles) on the weld flanges as the die closes The holding pressure requirement increases as the material gauge, strength and part complexity is increased. Sidewall and weld flange springback will also increase as material strength is increased. AHSS part designs should allow for an overbend component with open sidewall angles, otherwise added die processes will be required to make this correction to achieve finish part shape.

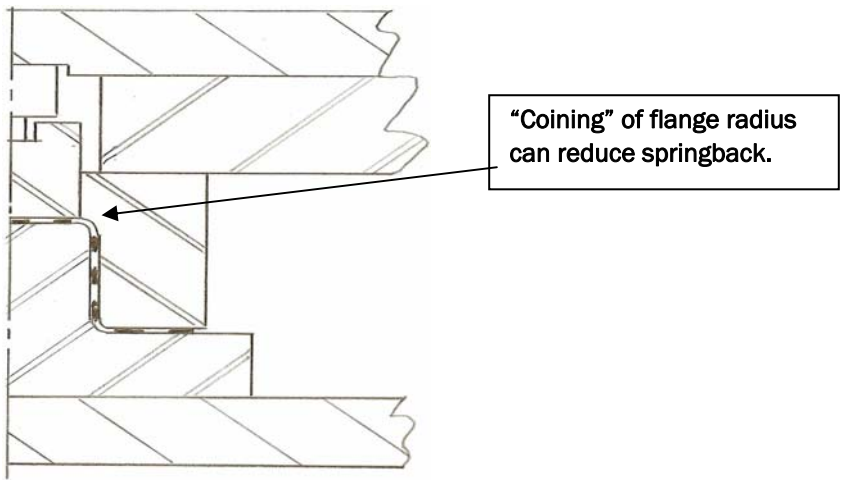


Figure 4.02 – Flange steel construction for coining the flange radius

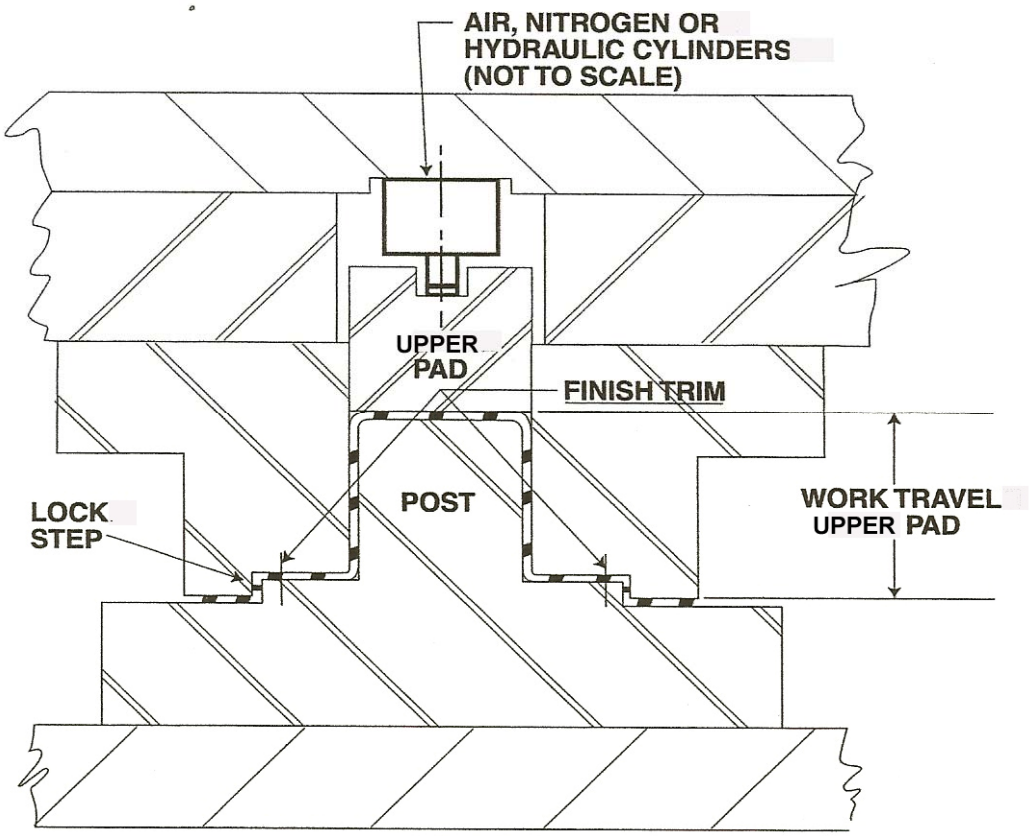


Figure 4.03 – Form Die, Post-Stretch (Upper Pad)

This variation of the form die process uses a solid lock step on the lower die. It is intended to stretch the part sidewalls to reduce sidewall curl. The amount of stretch will be determined by the depth of the lock step. The process is limited to those

applications without severe compression of metal in side walls and flanges, where overlapped metal could accumulate before the lockstep is engaged near the bottom of the stroke.

Note: This process has not been practical for some of the higher strength materials (above DP 600) because the radii of the lock step must be enlarged to avoid cracking as the material strength is increased.

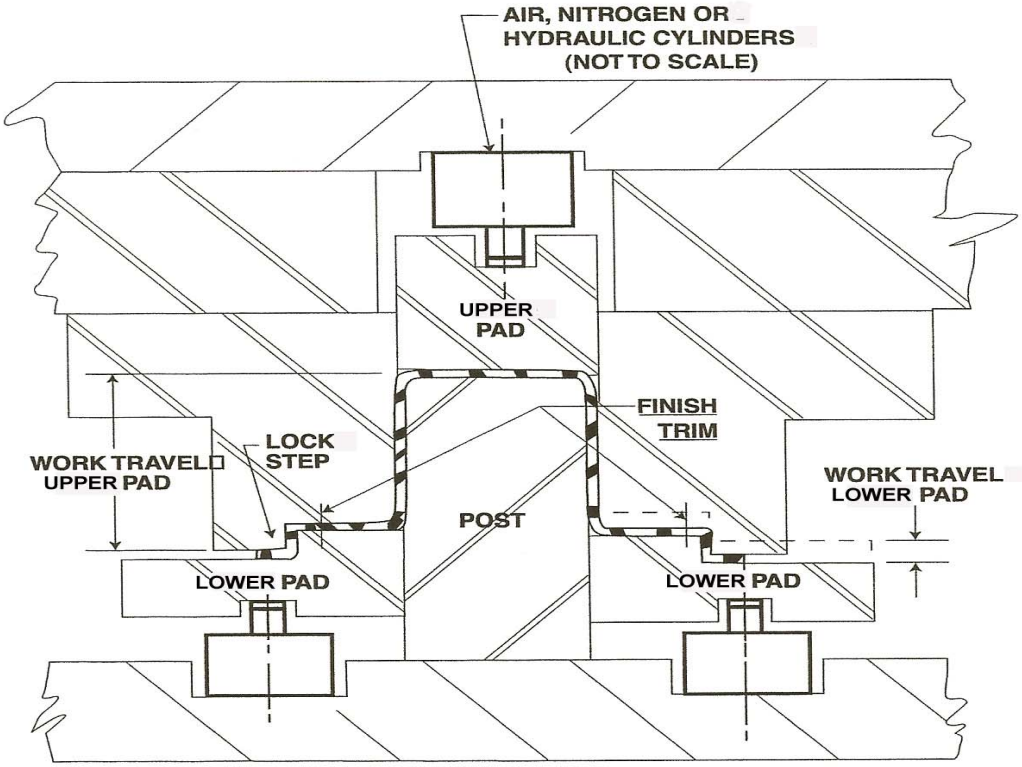


Figure 4.04 – Form Die, Post-Stretch (Upper and Lower Pads)

This die process uses a high pressure lower pad with a lock step to stretch the stamping over the die post before the die bottoms. The lower pad has only minimal travel, enough to stretch the part sidewalls at least 2%. The process is intended to reduce springback and sidewall curl of AHSS stampings.

Parts with severe compression of metal on sidewalls or flanges will require the lower pad restraining action for a greater portion of the part depth to avoid buckles and overlapped metal. In that case, draw beads may be used instead of the lock beads to allow metal to pull in from the restraining beads.

Note: A lower pad delayed-return system must be employed with these two-pad processes in order to avoid upstroke deformation of the part. This is usually done with a programmable hydraulic cushion in the press bed.

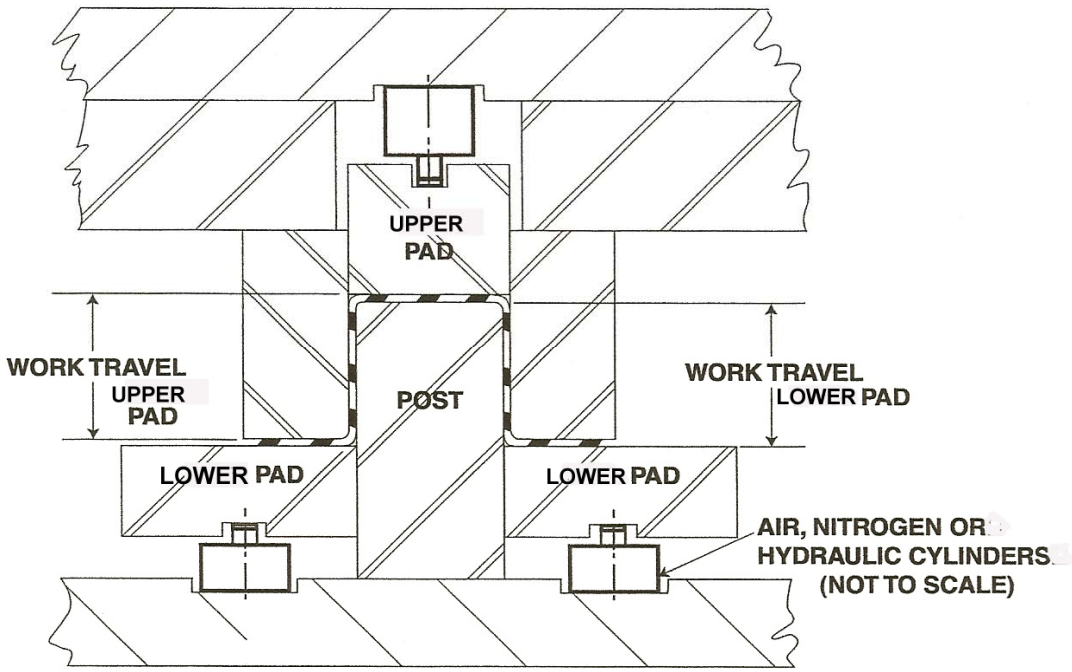


Figure 4.05 – Form Die, Draw Action (Upper and Lower Pads)

For high-strength steel parts with more complex geometry, a die process using upper and lower pads may be required. The upper pad holds the blank tight to the lower post to reduce buckling on the top surface as the die closes. Finished part shape can be on the binder surface. A pattern blank may be used without draw beads. If draw beads are used, a rough blank is required.

Note: A lower pad delayed-return system must be employed with these two-pad processes in order to avoid upstroke deformation of the part. This is usually done with a programmable hydraulic cushion in the press bed.

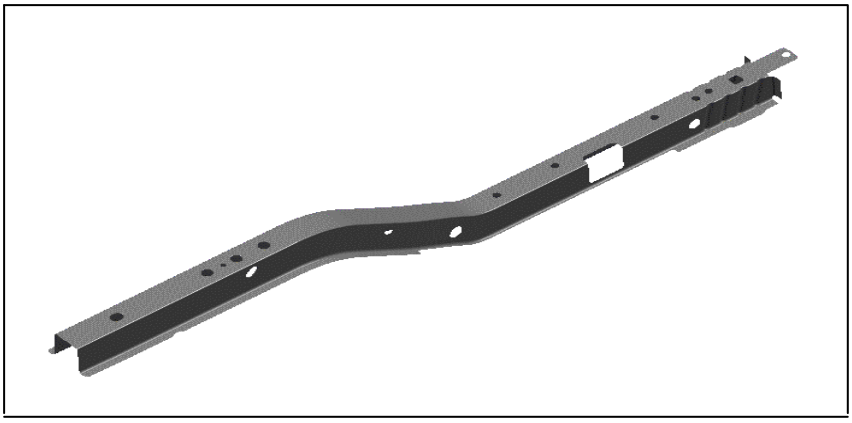


Figure 4.06 – Typical part design for stamping process shown in Figure 4.05

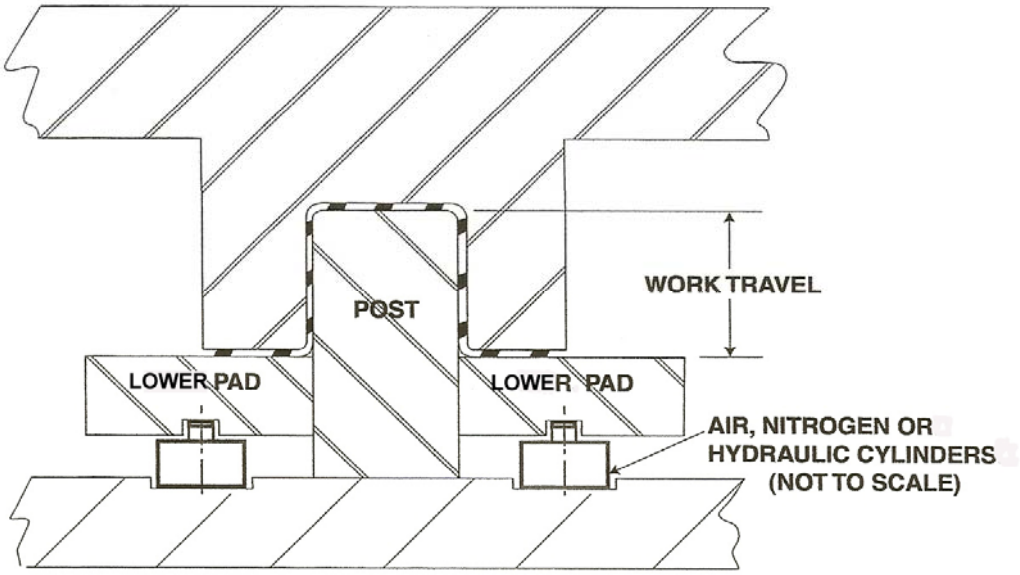


Figure 4.07 – Form Die, Draw Action (Lower Pad)

AHSS channel-shaped parts with severe compression flanges will require a lower pressure pad to control buckling in areas of metal compression. Part contours in the plan view or elevation can cause metal compression during the forming process. Buckling due to metal compression increases with higher strength steels and must be controlled with the proper die process.

This process is similar to a draw die, but is referred to as a "draw-action" form die when using a developed blank which eliminates the need for a trim die to remove binder

material. Part surfaces are on the binder. If a rough blank is used, draw beads can be employed as needed.

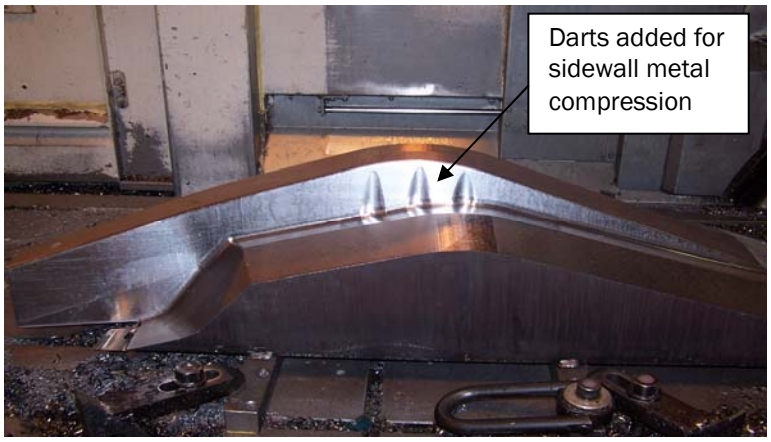


Figure 4.08 – Typical part design for form die, draw action process as shown in Figure 4.07

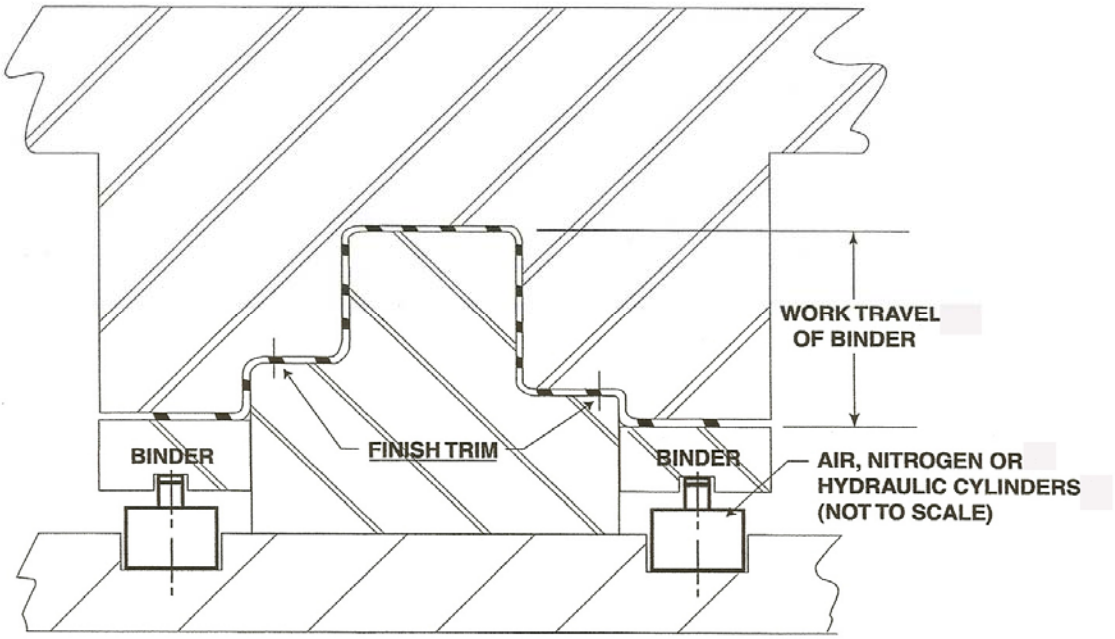


Figure 4.09 – Draw-Die, Single Action Press (Lower Binder)

Many AHSS parts with more severe plan view and elevation contours, and/or unequal length sidewalls, will require draw die operations. The binder pressure can be provided by die-mounted cylinders (shown above), a press bed pressure system or a double-action press. These processes use a rough blank and require a subsequent trim die operation to remove the binder scrap. Part surfaces are usually not on the binder

and draw beads are normally used. Another variation of this process would also have an upper pressure pad at the top of the channel section. (similar to Figure 4.05)

Note: Compensation for camber, twist and springback must be included in the draw die development. Residual stresses tend to be more severe in drawn stampings as opposed to formed stampings, therefore sidewall curl, twist and camber will be much more evident unless corrected in the draw development.

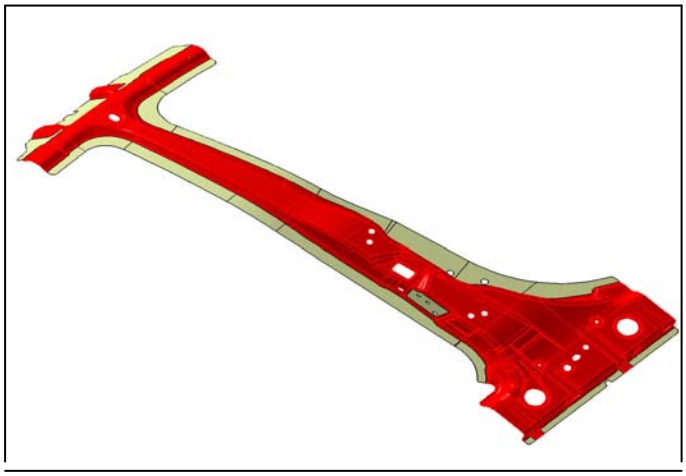


Figure 4.10 – Typical part design for stamping process shown in Sketch #6

Appendix

WorldAutoSteel

Section 2
Forming

Section 2 - Forming

2.A. General Comments

Forming of AHSS is not a radical change from forming conventional HSS. The major acquisition of new knowledge and experience needed for forming higher strength steels in general increased gradually over the years as ever-increasing strengths became available in the HSLA grades. Now new demands for improved crash performance, while reducing mass and cost, have spawned a new group of steels that improve on the current conventional base of HSS.

The AHSS solve two distinct automotive needs by two different groups of steels. The first group as a class has higher strength levels with improved formability and crash-energy absorption compared to the current HSLA grades. This requirement is fulfilled by the DP and TRIP grades of steel, which have increased values of the work hardening exponent. The second is to extend the availability of steel in strength ranges above the HSLA grades. This area is covered by the CP and MS grades. Originally targeted only for chassis, suspension, and body-in-white components, AHSS are now being applied to doors and other body panels. Additional steels highlighted previously in Figure 1-1B are designed to meet specific process requirements. These include increased edge stretch flangeability, strengthening after forming, or increased springback tolerances.

The improved capabilities the AHSS bring to the automotive industry do not bring new forming problems but certainly accentuate problems already existing with the application of any higher strength steel. These concerns include higher loads on presses and tools, greater energy requirements, and increased need for springback compensation and control. In addition, AHSS have greater tendency to wrinkle due to lack of adequate hold-down and often a reduction in sheet thickness.

The Applications Guidelines document utilizes a steel designation system to minimize regional confusion about the mechanical properties when comparing AHSS to conventional high-strength steels. The format is Steel Type YS/TS in MPa. Therefore, HSLA 350/450 would have minimum yield strength of 350 MPa and minimum tensile strength of 450 MPa. The designation also highlights different yield strengths for steel grades with equal tensile strengths, thereby allowing some assessment of the stress-strain curves and amount of work hardening.

Matching exact mechanical properties of the intended steel grade against the critical forming mode in the stamping not only requires an added level of knowledge by steel suppliers and steel users, but also mandates an increased level of communication between them. A specific example is total elongation versus local elongation. Total elongation has been the traditional measure of the steel's general stretchability over wide areas of the stamping – the required length of line deformation. Now, local elongation over very small gauge lengths found in stretch flanging, hole expansion, and blanked edge extension is as important as total elongation. The modification of microstructure to create DP and TRIP steels for increased work hardening exponent, greater stretchability and crash energy absorption, and higher total elongations reduces local elongation and edge stretchability – and vice versa.

New emphasis is being placed on determining specific needs of the stamping, highlighting critical forming modes, and identifying essential mechanical properties. The interaction of all inputs to the forming system means the higher loads and energy needs of AHSS also place new requirements on press capacity, tool construction/protection, lubricant capabilities, process design, and maintenance.

To this end, the Forming Section of these Guidelines addresses the mechanical properties, forming limits, and forming modes before covering the more traditional areas of tooling, springback, and press loads. Most data and experience are available for DP steels that have been in production and automotive use for some time. Less experience has been acquired with the TRIP steels that are now transitioning from the research phase to production.

2.B. Computerized Forming-Process Development

Using software to evaluate sheet metal formability has been in industrial use (as opposed to university and research environments) for more than a decade. The current sheet metal forming programs are part of a major transition to virtual manufacturing that includes analysis of welding, casting solidification, molding of sheet/fibre compounds, automation, and other manufacturing processes.

Computer simulation of sheet metal forming is identified more correctly as computerized forming-process development or even computerized die tryout. The more highly developed software programs closely duplicate the forming of sheet metal stampings as they would be done physically in the press shop.

For conventional steels, these programs have proven to be very accurate in blank movement, strains, thinning, forming severity, wrinkles, and buckles. Prediction of springback generally provides qualitatively helpful results. However, the magnitude of the springback probably will lack some accuracy and will depend highly on the specific stamping, the input information, and user experience.

Traditionally the software uses the simple power law of work hardening that treats the n value as a constant. For use with AHSS, the codes should treat the n value as a function of strain. Most commercial software now have the ability to process the true stress – true strain curve for the steel being evaluated without the need for a constitutive equation. However, this capability is not present in some proprietary industrial and university software and caution must be taken before using this software to analyze stampings formed from AHSS.

Computerized forming-process development is ideally suited to the needs of current and potential users of AHSS. A full range of analysis capabilities is available to evaluate AHSS as a new stamping analysis or to compare AHSS stampings to conventional Mild steel stampings. These programs allow rapid what-if scenarios to explore different grades of AHSS, alternative processing, or even design optimization.

The potential involvement of software-based AHSS process development is shown in Figure 2-1. At the beginning of the styling to production cycle, the key question is whether the stamping can even be made. With only the CAD file of the final part and material properties, the One-Step or Inverse codes can rapidly ascertain strain along section lines, thinning, forming severity, trim line-to-blank, hot spots, blank contour, and other key information.

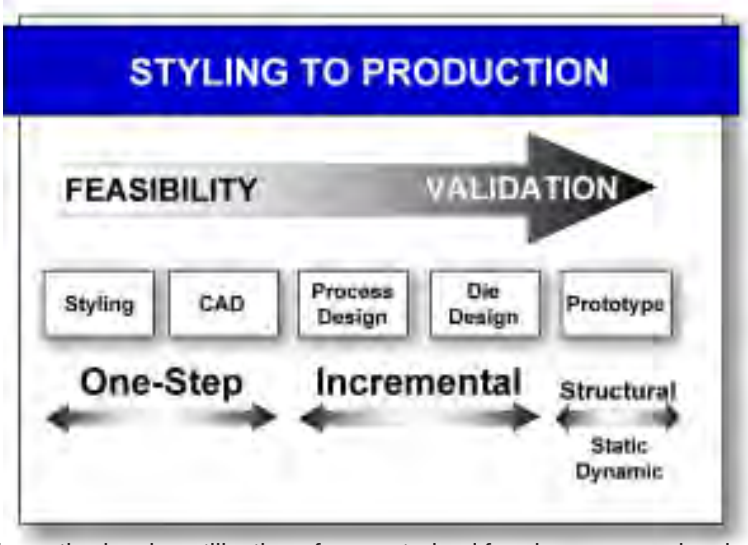


Figure 2-1 - Schematic showing utilization of computerized forming-process development to assist in forming stampings from AHSS.

During selection of process and die design parameters, the software will evaluate how each new input not only affects the outputs listed in the previous paragraph, but also will show wrinkles and generate a press-loading curve. The most useful output of the analysis is observing (similar to a video) the blank being deformed into the final part through a transparent die. Each frame of the video is equivalent to an incremental hit or breakdown stamping. Problem areas or defects in the final increment of forming can be traced backwards through the forming stages to the initiation of the problem. The most comprehensive software allows analysis of multi-stage forming, such as progressive dies, transfer presses, or tandem presses. The effects of trimming and other offal removal on the springback of the part are documented.

Since many applications of AHSS involve load bearing or crash analyses, computerized forming-process development has special utilization in structural analysis. Previously the part and assembly designs were analyzed for static and dynamic capabilities using CAD stampings with initial sheet thickness and as-received yield strength. Often the tests results from real parts did not agree with the early analyses because real parts were not analyzed. Now virtual parts are generated with point-to-point sheet thickness and strength levels nearly identical to those that will be tested when the physical tooling is constructed. Deficiencies of the virtual parts can be identified and corrected by tool, process, or even part-design before tool construction has even begun.

2.C. Sheet Forming

2.C.1. Mechanical Properties

By combining a number of different microstructures not traditionally found in conventional HSS, a wide range of properties are possible with AHSS. This allows steel companies to tailor the processing to meet the ever more focused application requirements demanded by the automotive industry.

Comparing these AHSS to their conventional HSS counterparts becomes much more difficult. The same minimum tensile strength can be found with a variety of steel types having different yield strengths. One example is TRIP 450/800, DP 500/800, and CP 700/800 steels with the same minimum tensile strength but with different yield strengths and typical total elongations in the range of 29%, 17%, and 13%, respectively. Some AHSS steels have their properties determined when the steel is produced. However, the properties of TRIP change during deformation as the retained austenite transforms to islands of martensite. The amount and rate of this transformation depends on the type and amount of deformation, the strain rate, the temperature of the sheet metal, and other conditions unique to the specific part, tool, and press. In contrast, a large range of HF and PFHT steel types generate their final properties though some form of quench operation only after forming has been completed.

AHSS property data contained in this section illustrate general trends and reasons why these trends differ from conventional HSS. Specific data can only be obtained by selecting the exact type, grade, and thickness of AHSS and then contacting the steel supplier for properties expected with their processing of the order. Data for the newer TWIP, FB, and HT steels are limited and therefore are only briefly noted.

Revised: 15 Mar 2009

2.C.1.a. Yield Strength - Total Elongation Relationships

A large range of yield strengths is available for the AHSS. Stretching is related to the total elongation obtained in a standard tensile test. Figure 2-2 shows the general relationship between yield strength and total elongation for AHSS compared to other high-strength steels.

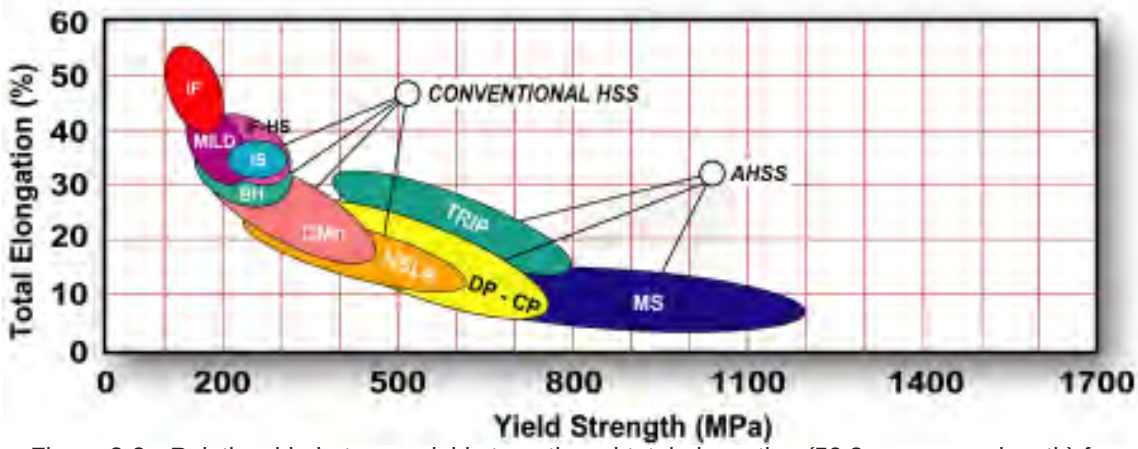


Figure 2-2 - Relationship between yield strength and total elongation (50.8 mm gauge length) for various types of steel.[I-1]

Note that the families of DP, CP, and TRIP steels generally have higher total elongations than HSLA steels of equal yield strengths.

Most AHSS steels have no yield point elongation. Some samples of higher strength DP grades and TRIP steels may show YPE but the value typically should be less than 1%. These values are in contrast with various HSLA grades, which can have YPE values greater than 5%.

2.C.1.b. Tensile Strength - Total Elongation Relationships

The relationship between ultimate tensile strength and total elongation for the various types of steels in Figure 2-3 parallels that observed in Figure 2-2.

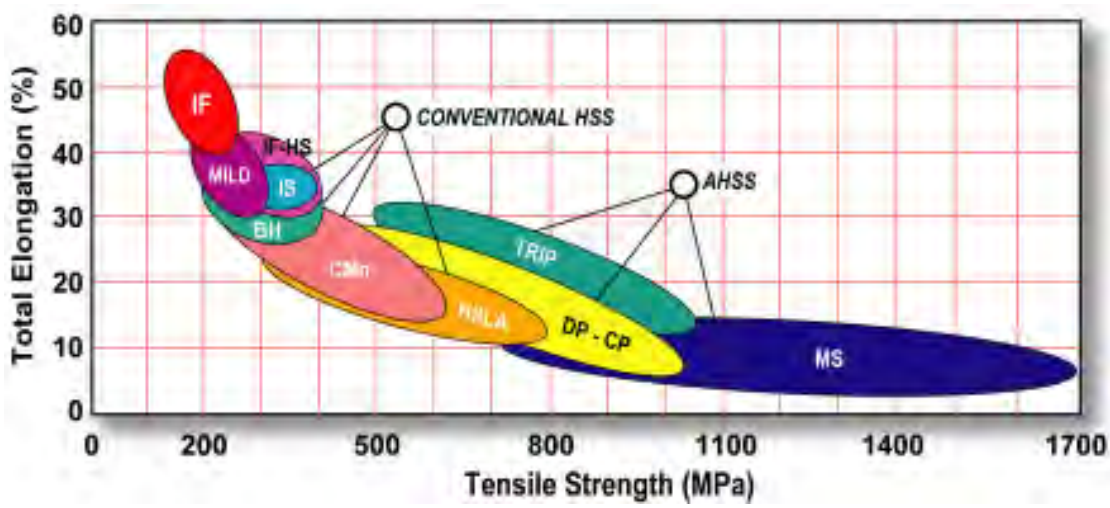


Figure 2-3 - Relationship between ultimate tensile strength and total elongation (50.8 mm gauge length) for various types of steel.[I-1]

When ordering steel based on tensile strength, the DP, CP, and TRIP steels in general still have higher total elongations than HSLA steels of equal tensile strengths. Total elongation information for the newer TWIP, FB, HF, and PFHT steels are presented in Section 1, Figure 1-1B.

2.C.1.c. Work Hardening Exponent (n-value)

Sheet metal stretchability is strongly influenced by the work hardening exponent or n-value. The capabilities of the n-value are schematically illustrated in Figure 2-4.

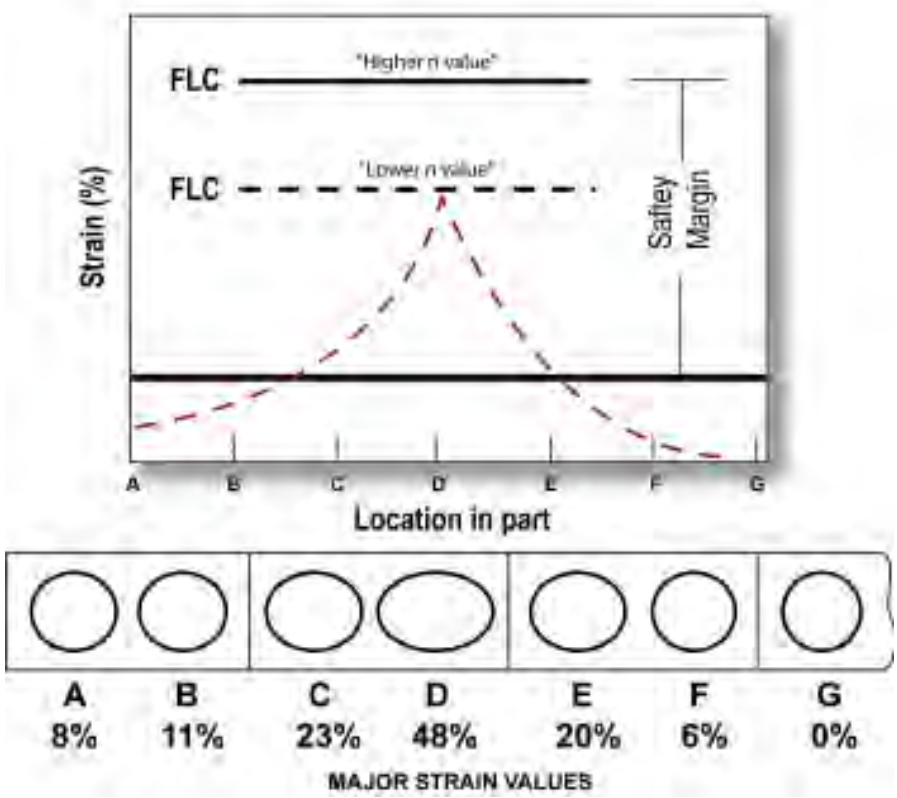


Figure 2-4 - Schematic showing the safety margin between allowable FLC strain for a higher n-value (solid line) and a lower n-value (dashed line).

The n-value is the key parameter in determining the maximum allowable stretch as determined by the Forming Limit Curve (FLC). The height of the FLC is directly proportional to the terminal n-value as discussed later. The n-value also contributes to the ability of steel to distribute the strain more uniformly in the presence of a stress gradient. The higher the n-value, the flatter the strain gradient. A higher n-value (solid lines in Figure 2-4) compared to a lower n-value (dashed lines) means a deeper part can be stretched for equal safety margins or a larger safety margin for equal depth parts.

The decreasing n-value with increasing yield strength for conventional HSS (Figure 2-5) limits the application of some HSS.

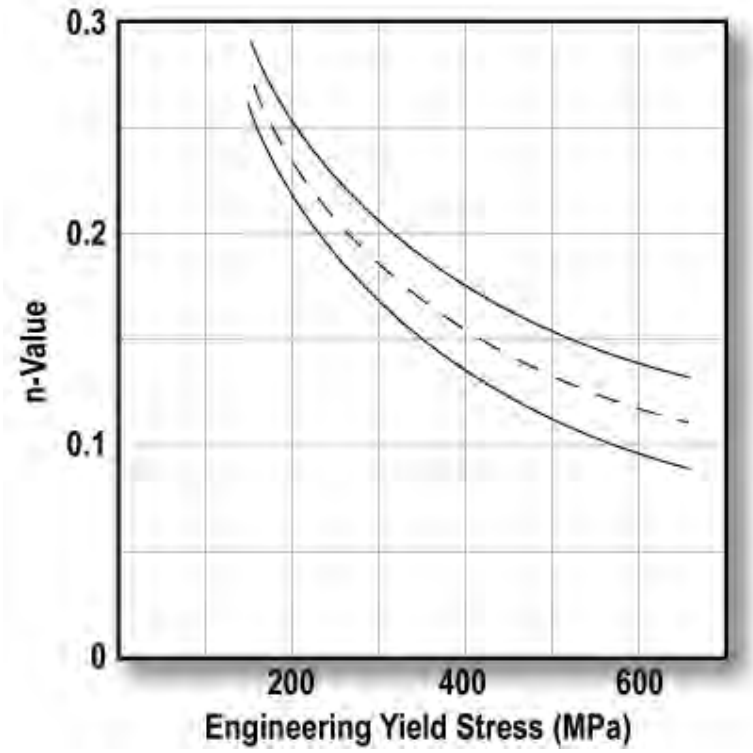


Figure 2-5 - Experimental relationship between n-value (work hardening exponent measured from 10 to 20% strain) and engineering yield stress for a wide range of Mild steel and conventional HSS types and grades.[K-2]

Unfortunately, comparison of n-value for DP steel to HSLA steel requires more than comparing the two single values of n for a given yield strength. The following tensile test data show why. In one study, the HSLA 350/450 has a 0.14 n-value and the DP 350/600 has an identical 0.14 n-value in a standard test procedure measuring the n-value over a strain range of 10% to 20%. No differences are reported, which is contrary to increased stretchability gained when using DP steels. On the other hand, a number of different DP steels showing a wide range of n-values were observed for a given strength level.

Unlike the HSLA 350/450 steel that has an approximately constant n-value over most of its strain range, the n-value for the DP 350/600 starts higher and then decreases with increasing strain as the initial effect of the original martensite islands is diminished. To capture this behaviour, the instantaneous n-value as a function of strain must be determined.

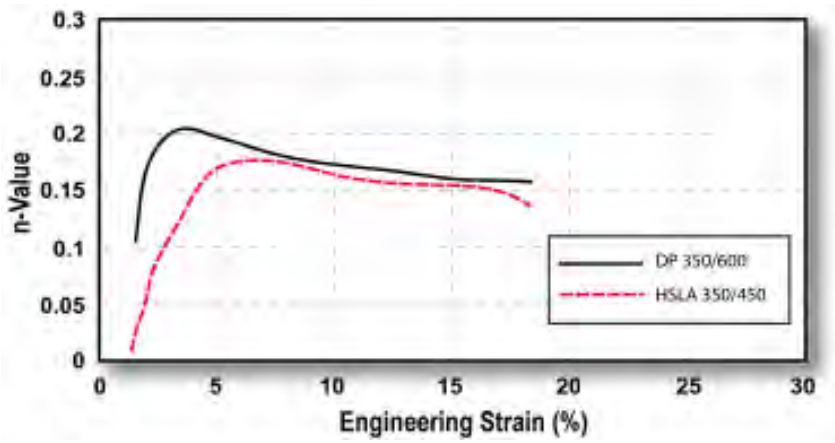


Figure 2-6 - Instantaneous n values versus strain for DP 350/600 and HSLA 350/450 steels.[K-1]

The instantaneous n-value curves for the HSLA 350/450 and DP 350/600 shown in Figure 2-6 clearly indicate the higher n-value for DP steel for strain values less than 7%. The higher initial n-value tends to restrict the onset of strain localization and growth of sharp strain gradients. Minimization of sharp gradients in the length of line also reduces the amount of localized sheet metal thinning. The approximately constant n-value plateau extending beyond the 10% strain range provides the terminal or high strain n-value. This terminal n-value is a major input in determining the maximum allowable strain in stretching as defined by the forming limit curve.

This reduction in thinning for a channel is presented in Figure 2-7. Substitution of DP 350/600 for HSLA 350/450 reduced the maximum thinning from 25% to 20%. The instantaneous n-values for these two steels are shown in Figure 2-6.

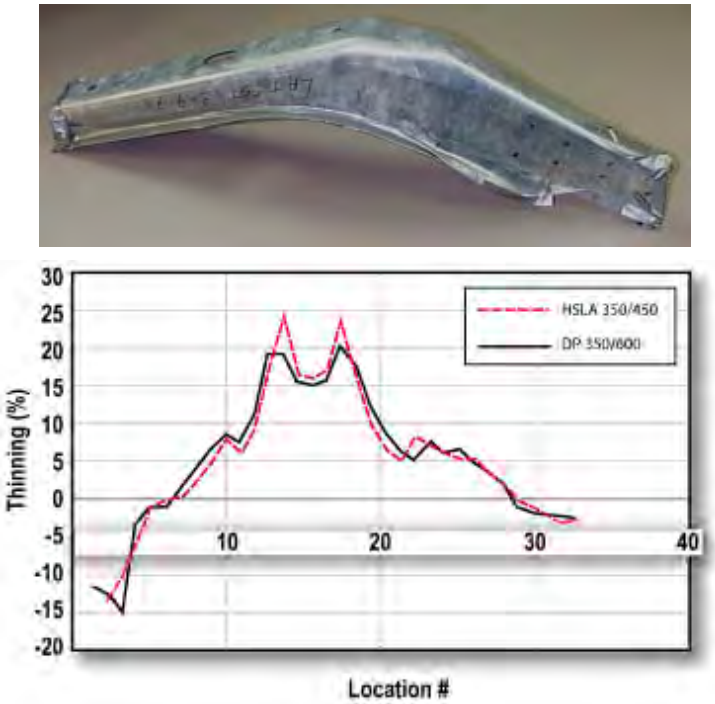


Figure 2-7 - Thinning strain distribution for a channel produced with DP and HSLA steels.[S-1]

Unlike the DP steels where the increase in n-value is restricted to the low strain-values, the TRIP steels constantly create new islands of martensite as the steel is deformed to higher strain-values. These new martensite islands maintain the high value of n as shown in Figure 2-8.

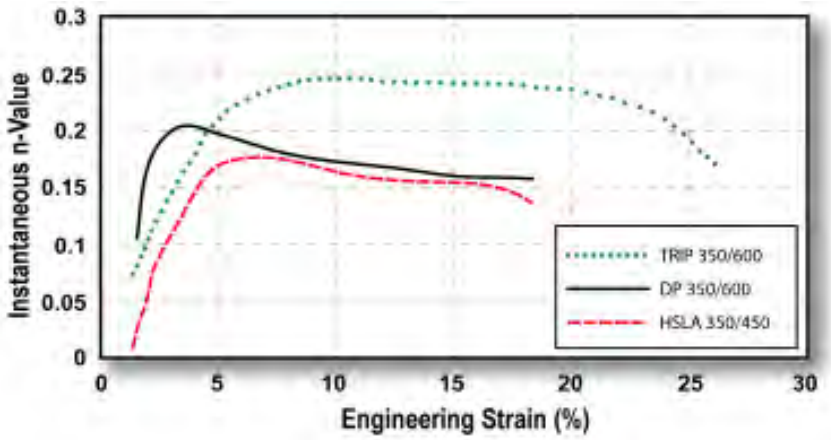


Figure 2-8 - Instantaneous n values versus strain for TRIP, DP, and HSLA steels.[K-1]

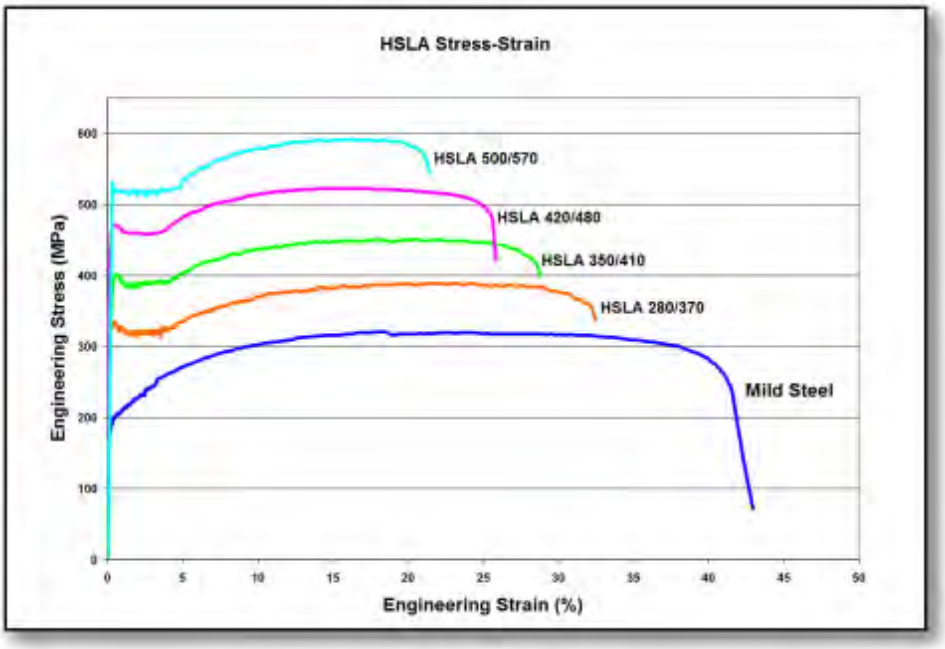
The continued high n-value of the TRIP steel relative to the HSLA steel contributes to the increase in total elongation observed in Figures 2-2 and 2-3. The increased n-value at higher strain levels further restricts strain localization and increases the height of the forming limit curve.

The n values for TWIP have been described [C-4] as increasing to 0.4 at an approximate strain of 30% due to the twinning mode of deformation and then remaining constant until a total elongation of 52%. In contrast, the formability properties of the HF steels are only developed after the blanks reach operating temperature.

2.C.1.d. Stress-Strain Curves

Stress-strain curves are extremely valuable for comparing different steel types and even different grades within a single type of steel. Engineering stress–engineering strain curves are developed using initial gage length and initial cross-sectional area of the specimen. These curves highlight yield point elongation, ultimate tensile strength, uniform elongation, total elongation, and other strain events. In contrast, the true stress–true strain curves are based on instantaneous gage length and instantaneous cross-sectional area of the specimen. Therefore, the area under the curve up to a specific strain is proportional to the energy required to create that level of strain or the energy absorbed (crash management) when that level of strain is imparted to a part.

Figure 9 is a collection of typical stress-strain curves – both engineering and true – for different grades of HSLA, DP, TRIP, CP, and MS steels. True stress-strain curves only are presented for HF steels in Figure 2-10. A typical stress-strain curve for Mild steel is included in each graph for reference purposes. This will permit one to compare potential forming parameters, press loads, press energy requirements, and other parameters when switching among different steel types and grades.



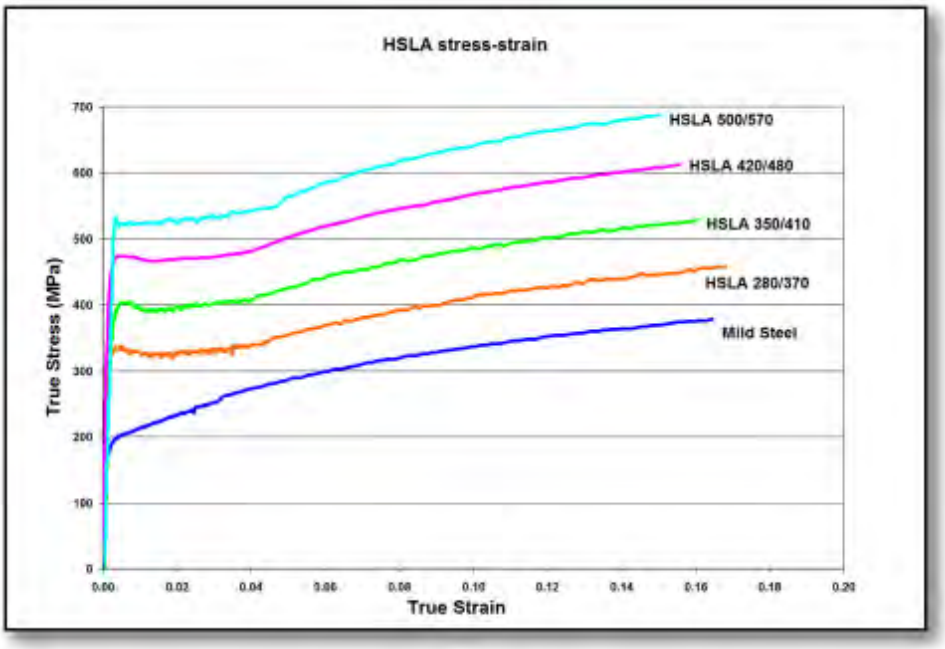
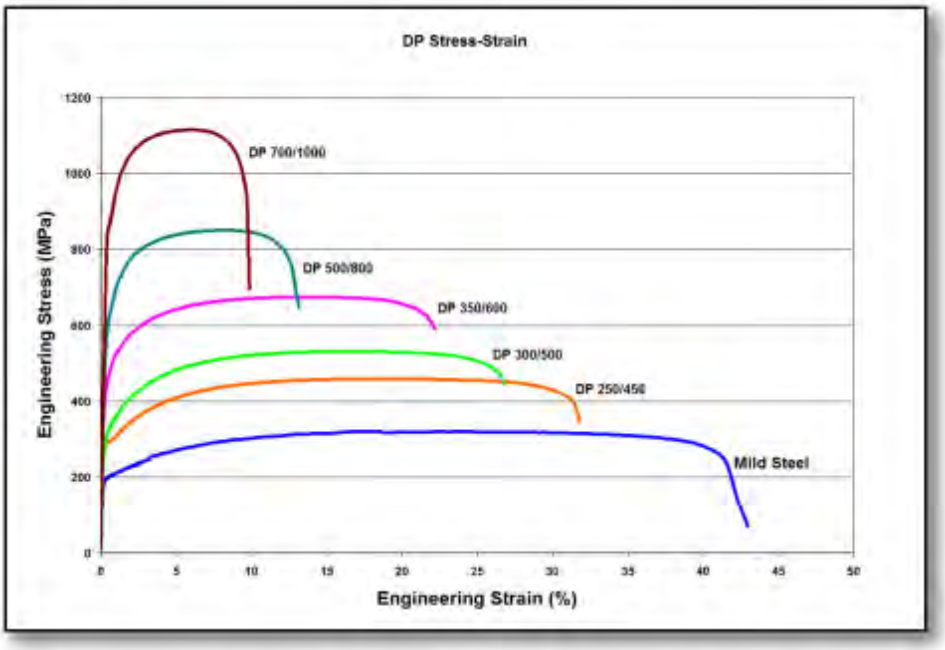


Figure 2-9A – Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curves for a series of cold-rolled HSLA steel grades.[S-5]



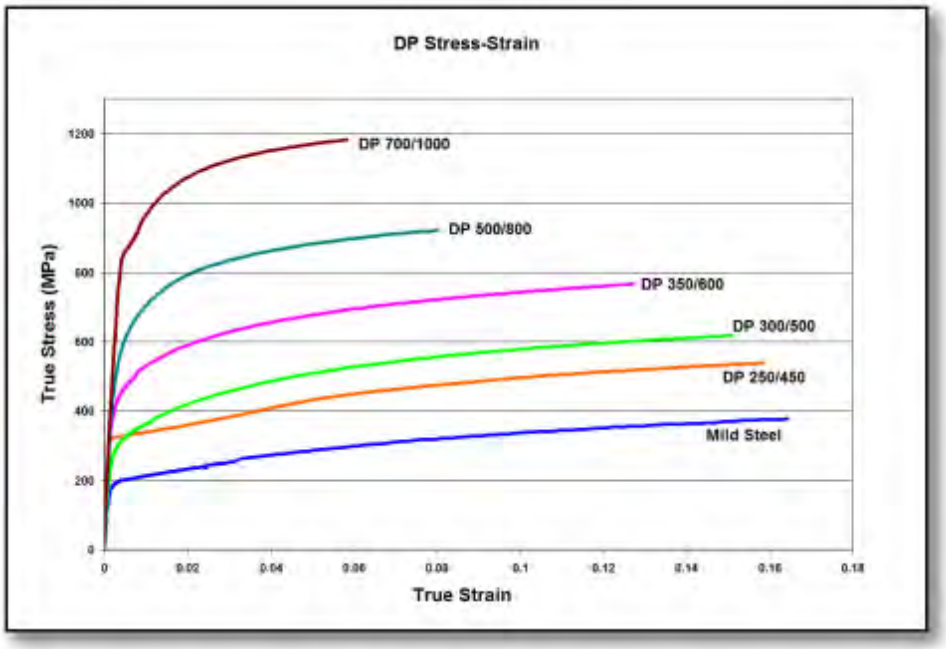
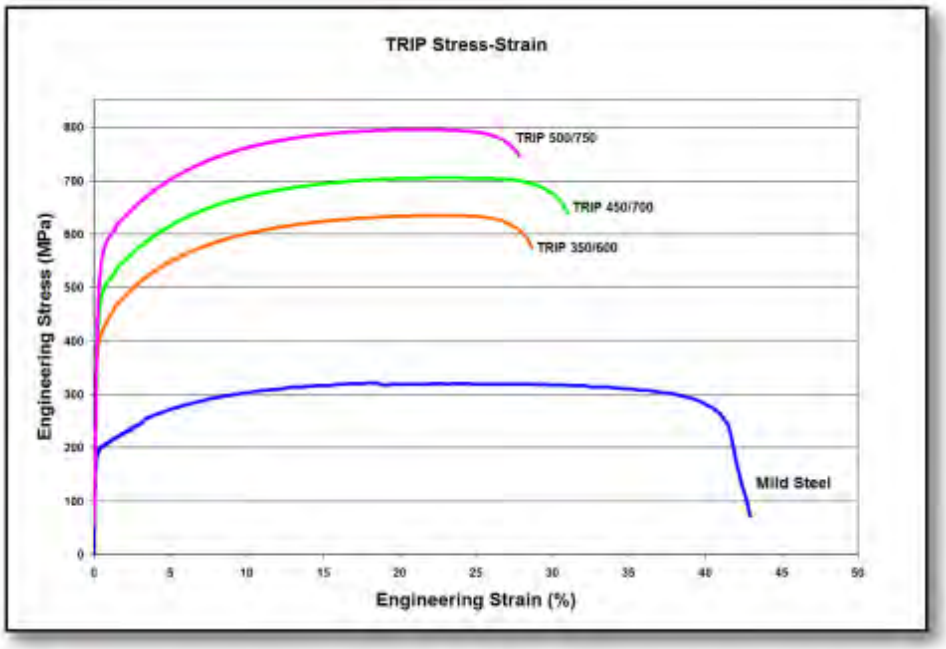


Figure 2-9B – Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curves for a series of DP steel grades.[S-5, V-1] Sheet thicknesses: DP 250/450 and DP 500/800 = 1.0mm. All other steels were 1.8-2.0mm.



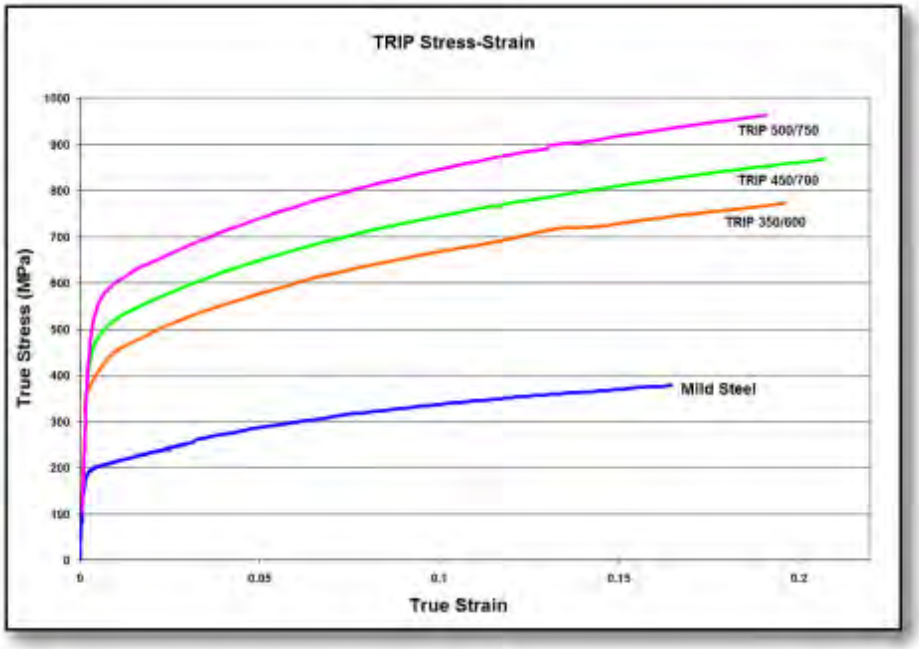
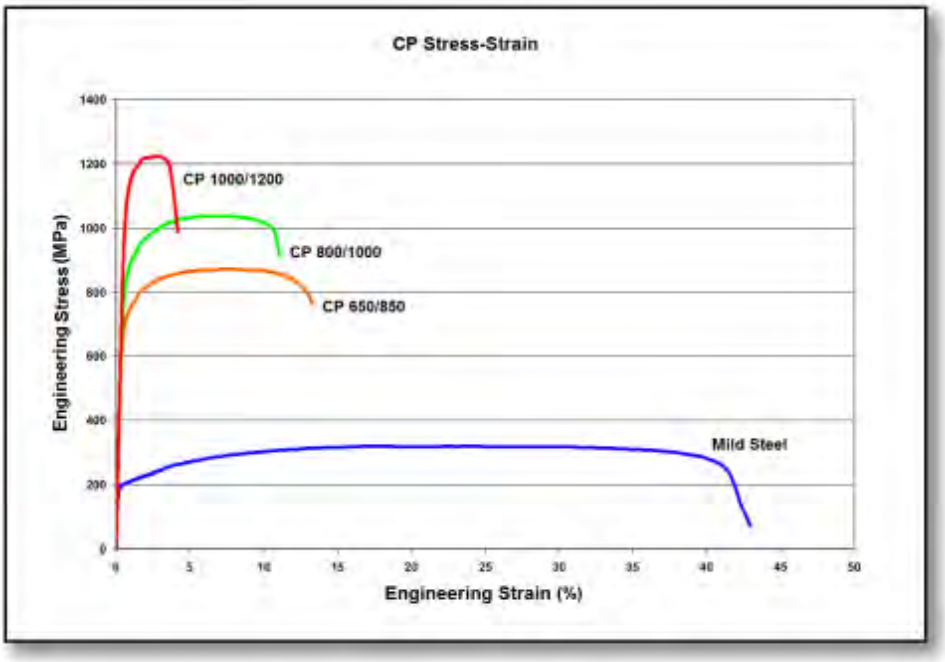


Figure 2-9C – Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curves for a series of TRIP steel grades.[V-1] Sheet thickness: TRIP 350/600 = 1.2mm, TRIP 450/700 = 1.5mm, TRIP 500/750 = 2.0mm, and Mild Steel = approx. 1.9mm.



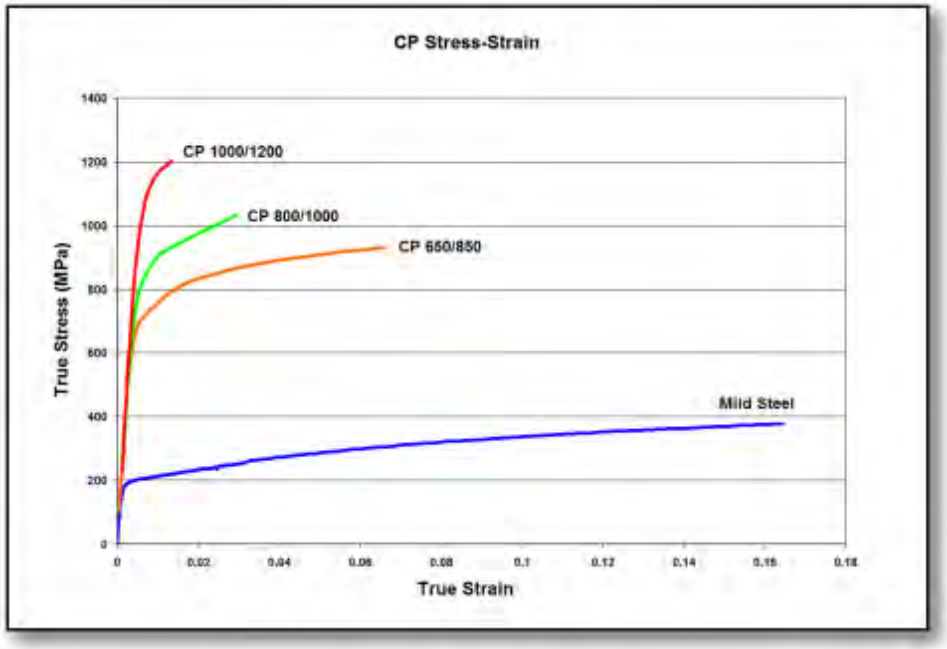
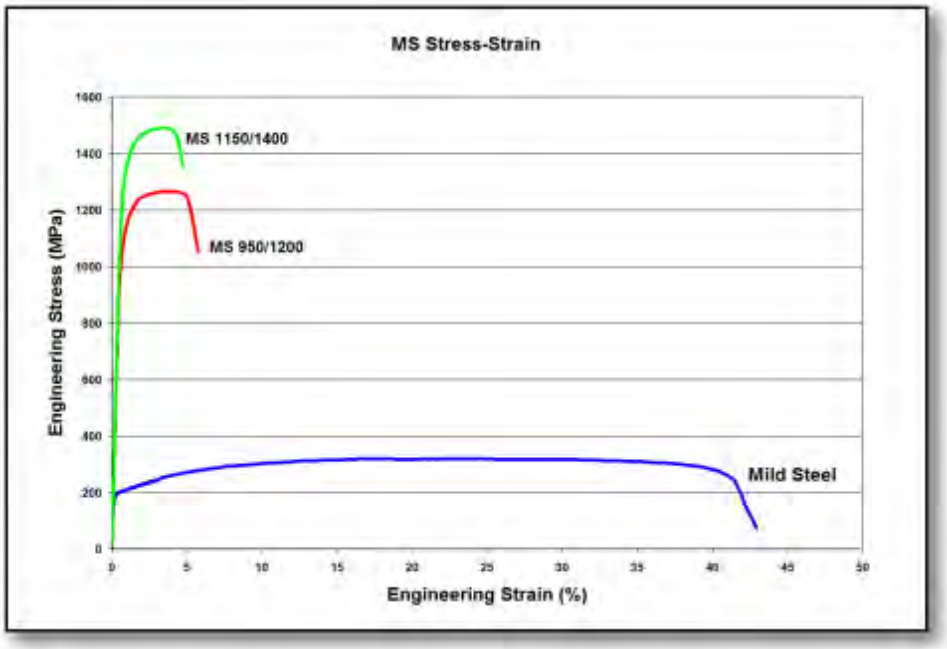


Figure 2-9D – Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curves for a series of CP steel grades.[V-1] Sheet thickness: CP650/850 = 1.5mm, CP 800/1000 = 0.8mm, CP 1000/1200 = 1.0mm, and Mild Steel = approx. 1.9mm.



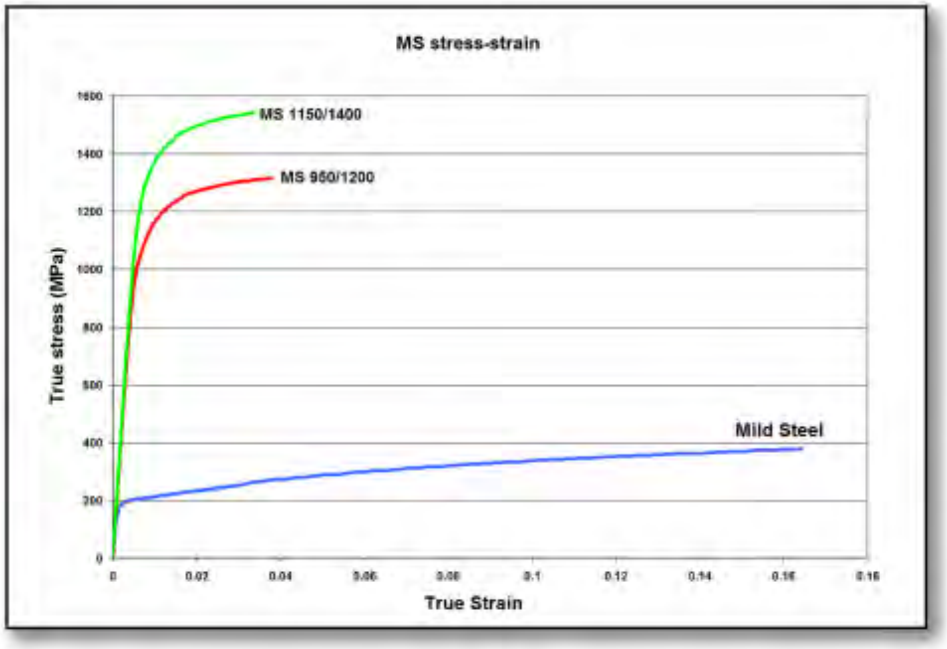
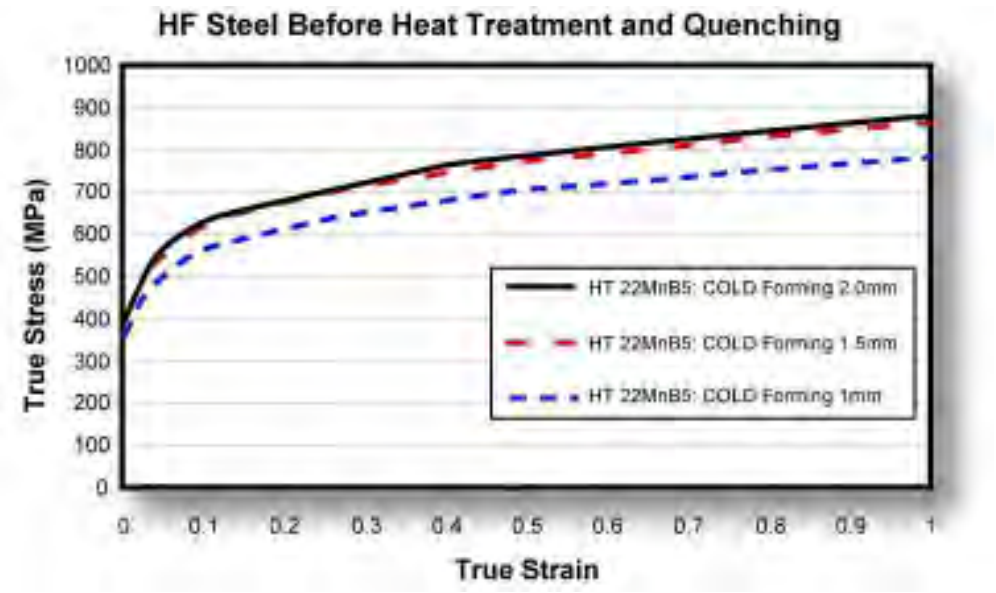


Figure 2-9E – Engineering stress-strain (upper graphic) and true stress-strain (lower graphic) curves for a series of MS steel grades.[S-5] All Sheet thicknesses were 1.8-2.0mm.



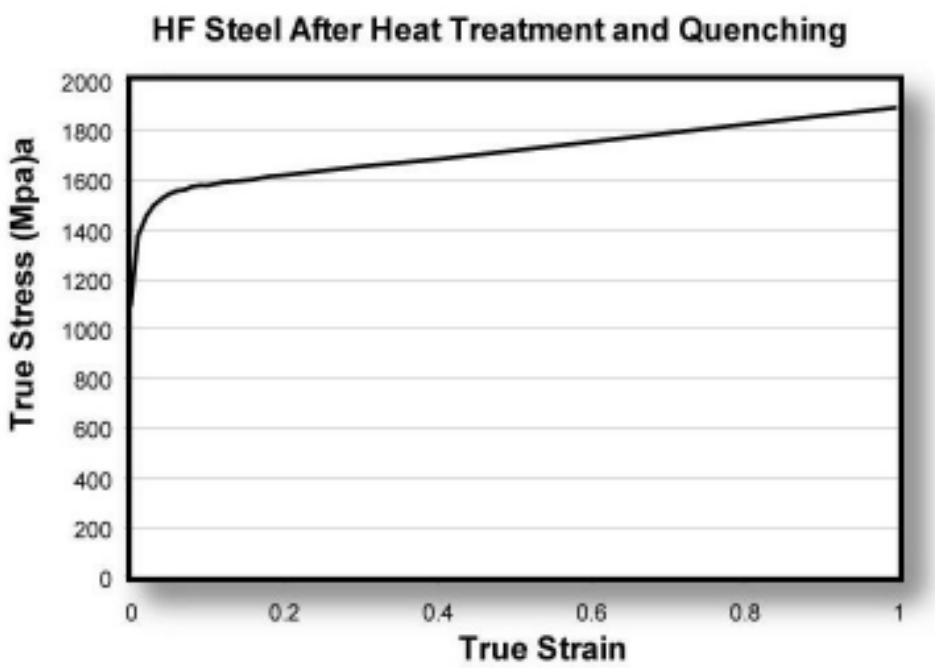


Figure 2-10 – True stress-strain curves for different sheet thickness of as-received boron-based HF steel tested at room temperature (upper curve) and tested after heat treatment and quenching (lower curve).[V-1]

2.C.1.e. Normal Anisotropy Ratio ($\bar{r}$ or r_m)

The normal anisotropy ratio (r_m) defines the ability of the metal to deform in the thickness direction relative to deformation in the plane of the sheet. For r_m values greater than one, the sheet metal resists thinning. Values greater than one improve cup drawing, hole expansion, and other forming modes where metal thinning is detrimental.

High-strength steels with UTS greater than 450 MPa and hot-rolled steels have r_m values approximating one. Therefore, HSS and AHSS at similar yield strengths perform equally in forming modes influenced by the r_m value. However, r-value for higher strength grades of AHSS (800 MPa or higher) can be lower than one and any performance influenced by r-value would be not as good as HSLA of similar strength.

2.C.1.f. Strain Rate Effects

To characterize the strain rate sensitivity, medium strain rate tests were conducted at strain rates ranging from 10^{-3}/sec (commonly found in tensile tests) to 10^{3}/sec. For reference, 10^{1}/sec approximates the strain rate observed in a typical stamping. As expected, the results showed that YS (Figure 2-11) and UTS (Figure 2-12) increase with increasing strain rate.

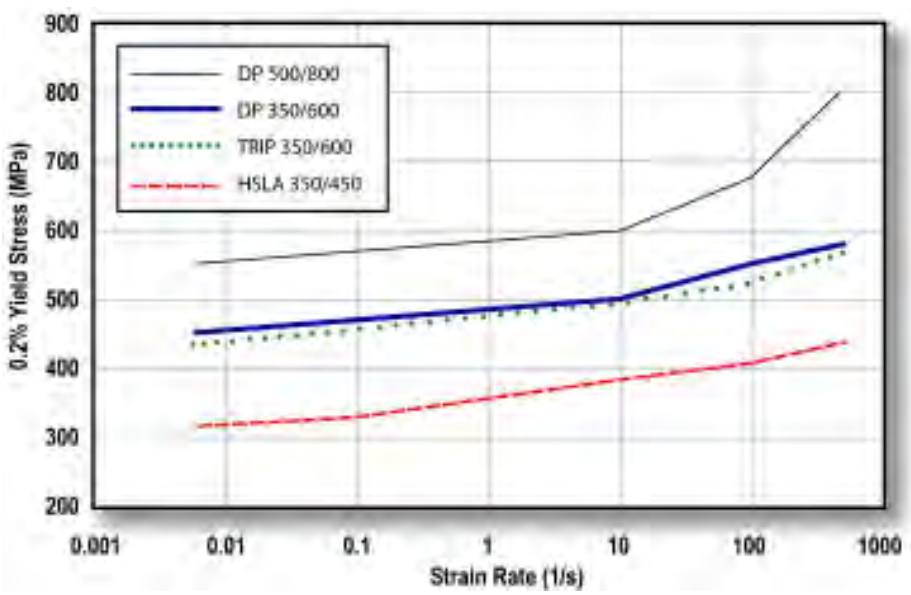


Figure 2-11 - Increase in yield stress as a function of strain rate.[Y-1]

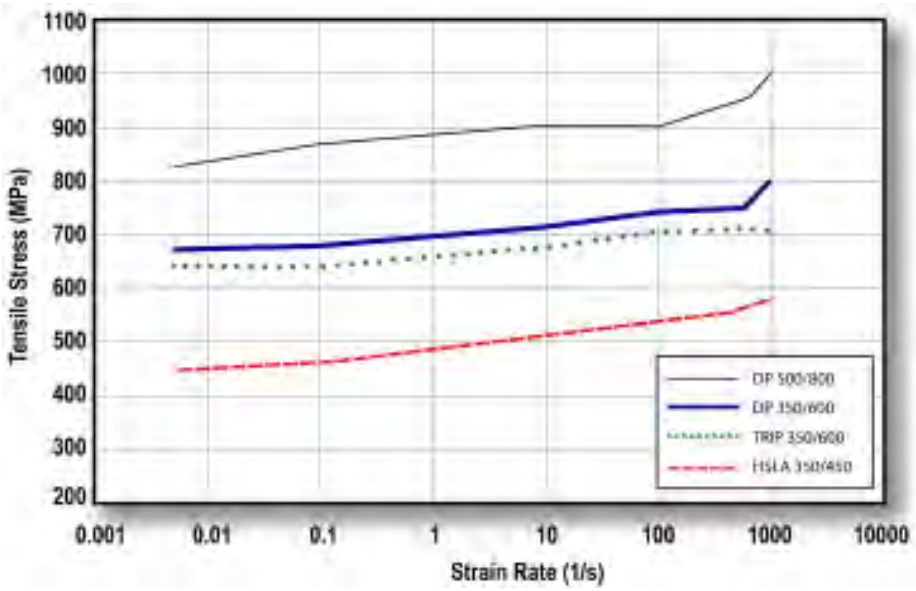


Figure 2-12 - Increase in tensile stress as a function of strain rate.[Y-1]

However, up to a strain rate of 10^1/sec, both the YS and UTS only increased about 16-20 MPa per order of magnitude increase in strain rate. These increases are less than those measured for low strength steels. This means the YS and UTS values active in the sheet metal are somewhat greater than the reported quasi-static values traditionally reported. However, the change in YS and UTS from small changes in press strokes per minute are very small and are less than the changes experienced from one coil to another.

The change in n-value with increase in strain rate is shown in Figure 2-13. Steels with YS greater than 300 MPa have an almost constant n-value over the full strain rate range, although some variation from one strain rate magnitude to another is possible.

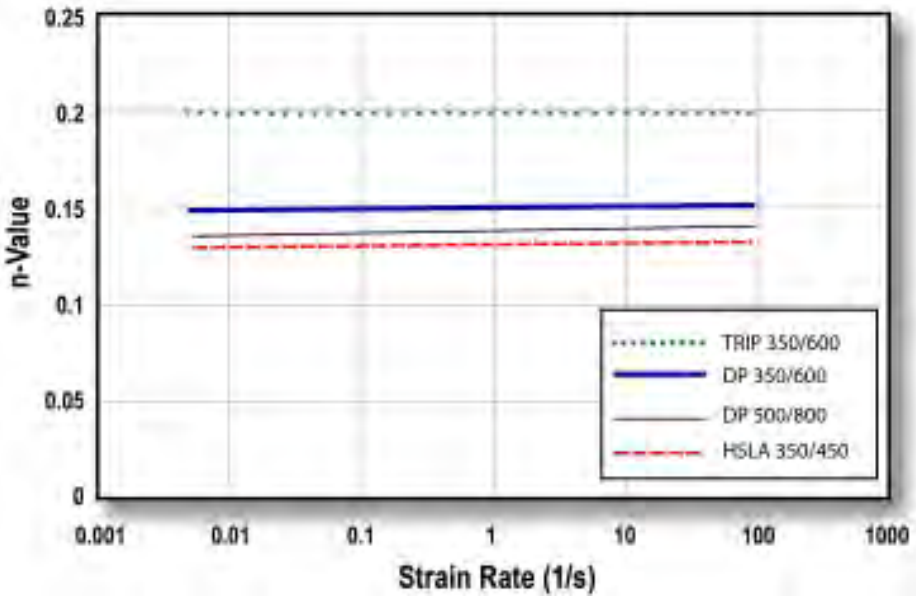


Figure 2-13 - Relationship between n-value and strain rate showing relatively no overall increase.[Y-1]

Figure 2-14 shows the true stress-true strain curves at several strain rates for HF steel after heat treatment and quenching. The yield stress increases approximately five MPa for one order of magnitude increase in strain rate.

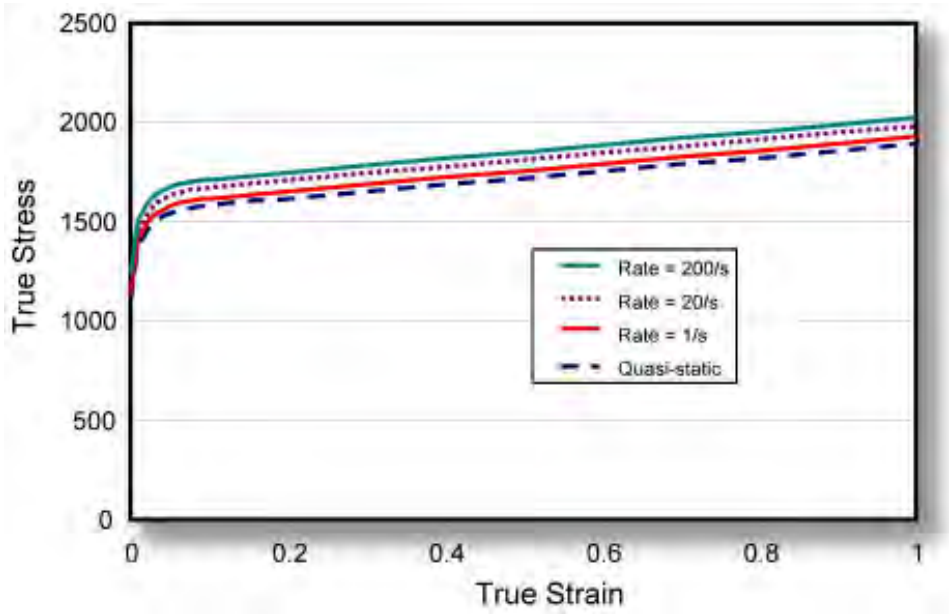


Figure 2-14 – Extended true stress-strain curves for different strain rates.[V-1] Steel is 1.0 mm thick HF after heat treatment and quenching.

2.C.1.g. Bake Hardening and Aging

Strain aging was measured using typical values for an automotive paint/bake cycle consisting of 2% uniaxial pre-strain followed by baking at 170 °C for 30 minutes. Figure 2-15 defines the measurement for work hardening (B minus A), unloading to C for baking, and reloading to yielding at D for measurement of bake hardening (D minus B).

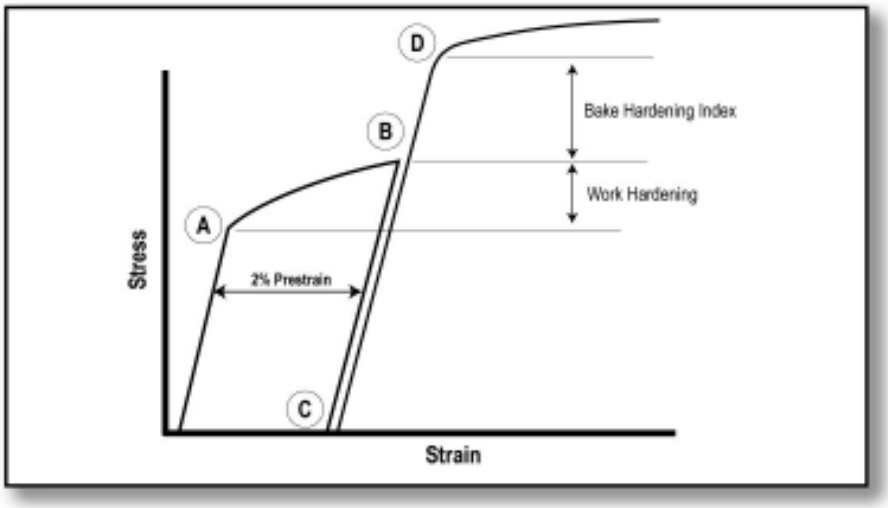


Figure 2-15 - Measurement of work hardening index and bake hardening index.

Figure 2-16 shows the work hardening and bake hardening increases for the 2% prestrained and baked tensile specimen. The HSLA shows little or no bake hardening, while AHSS such as DP and TRIP steels show a large positive bake hardening index. The DP steel also has significantly higher work hardening than HSLA or TRIP steel because of higher strain hardening at low strains. No aging behaviour of AHSS has been observed due to storage of as-received coils or blanks over a significant length of time at normal room temperatures. Hence, significant mechanical property changes of shipped AHSS products during normal storage conditions are unlikely.

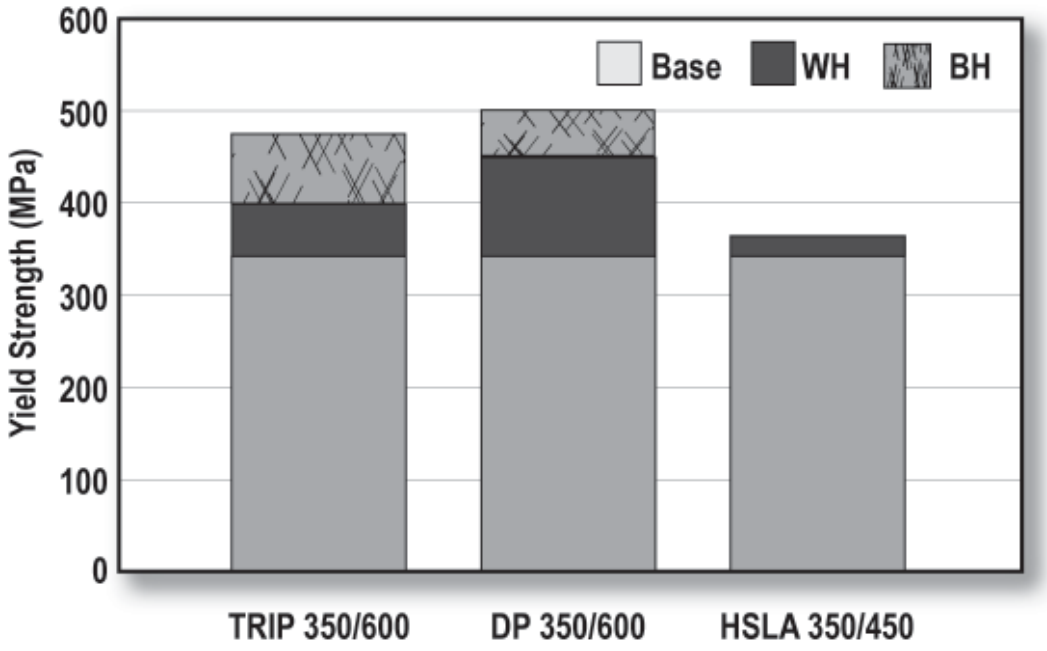


Figure 2-16 - Comparison of work hardening (WH) and bake hardening (BH) for TRIP, DP, and HSLA steels given a 2% prestrain.[S-1, K-3]

2.C.1.h. Key Points

- AHSS generally have greater total elongations compared to conventional HSS of equal ultimate tensile strengths.
- DP steels have increased n-values in the initial stages of deformation compared to HSS. These higher n-values help distribute deformation more uniformly in the presence of a stress gradient and thereby reduce local thinning.
- TRIP steels have less initial increase in n-value than DP steels but sustain the increase throughout the entire deformation process. These AHSS can have n-values comparable to Mild steels.
- Most cold-rolled and coated AHSS and HSS steels with UTS greater than 450 MPa and all hot-rolled steels have normal anisotropy values (r_m) around a value of one.
- YS and UTS for AHSS increase only about 16-20 MPa per ten-fold increase in strain rate, which is less than Mild steel increases. The n-value changes very little over a 10^5 increase in strain rate.
- As-received AHSS does not age-harden in storage.
- DP and TRIP steels have substantial increase in YS due to a bake hardening effect, while HSLA steels have almost none.

2.C.2. Forming Limits

Knowledge of forming limits is important throughout the entire product design to production cycle. First is the computerized forming-process development (virtual die tryout), which requires forming limits for the selected steel type and grade to assess the forming severity (hot spots) for each point on the stamping. Next is the process and tool design stage where specific features of the tooling are established and again computer-validated against forming limits for the specific steel. Troubleshooting tools for die tryout on the press shop floor utilize forming limits to assess the final severity of the part and to track process improvements. Finally, forming limits are used to track part severity throughout the production life of the part as the tooling undergoes both intentional (engineering) modifications and unintentional (wear) changes.

This sub-section presents three different types of forming limits. First is the traditional forming limit curve that applicable to all modes of sheet metal forming. Second is a sheared edge stretching limit that applies to the problem of stretching (hole expansion, stretch flanging) the cut edge of sheet metal. Third is shear fracture encountered during small radii bending of DP and TRIP steels.

2.C.2.a. Forming Limit Curves (FLC)

Forming limit curves (FLC) are used routinely in many areas around the world during the design, tryout, and production stages of a stamping. An FLC is a map of strains that indicate the onset of critical local necking for different strain paths, represented by major and minor strains. These critical strains not only become the limit of useful deformation but are also the points below which safety margins are calculated.

Experimental determination of FLCs involves forming sheet specimens of different widths to generate different strain paths and measuring the different critical strains. Considerable prior work has been done with respect to characterizing the minimum value of the FLC as a function on n-value and thickness for different steel types and grades. One equation for FLC_0 is given in Figure 2-17. Regional differences may be observed in the generation, shape, and application of forming limit curves.

Examples of experimental FLCs are shown in Figure 2-17 for Mild Steel 170/300, HSLA 350/450, and DP 350/600 with sheet thicknesses equal to 1.2 mm. All three curves have approximately the same shape and the minimum value of the major strain generally is predictable from the FLC_0 equation. Since the HSLA and DP steels have approximately the same terminal (high strain) n value (Figure 2-6), the identical FLCs were expected. The Mild Steel has an elevated FLC because its terminal n value is substantially higher than the HSLA and DP steels tested.

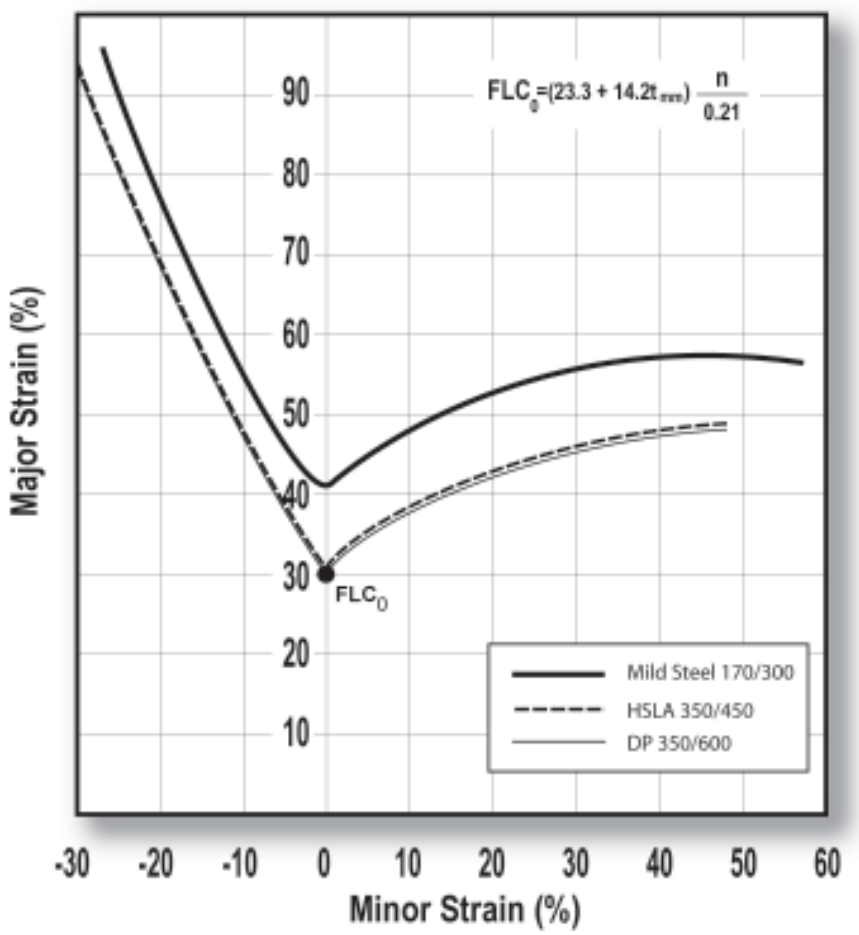


Figure 2-17- Experimental FLCs for one sample each of Mild, HSLA, and DP steels with thicknesses equal to 1.2 mm.[K-1]

Determination of FLCs for TRIP and MS steels (Figure 2-18) present additional problems and need further development. For example, the terminal n value of the TRIP steels depends strongly on different chemistries and processing used by different steel producers. In addition, the terminal n value is a function of the strain history of the stamping that determines the transformation of retained austenite to martensite. Since different locations in a stamping follow different strain paths (balanced biaxial, plane strain, uniaxial tension, compression, etc.) and varying amounts of deformation, the terminal n for TRIP steel could vary not only from part design to part design but also with location within the part. The MS steels have very little available deformation, which makes generation of FLCs difficult.

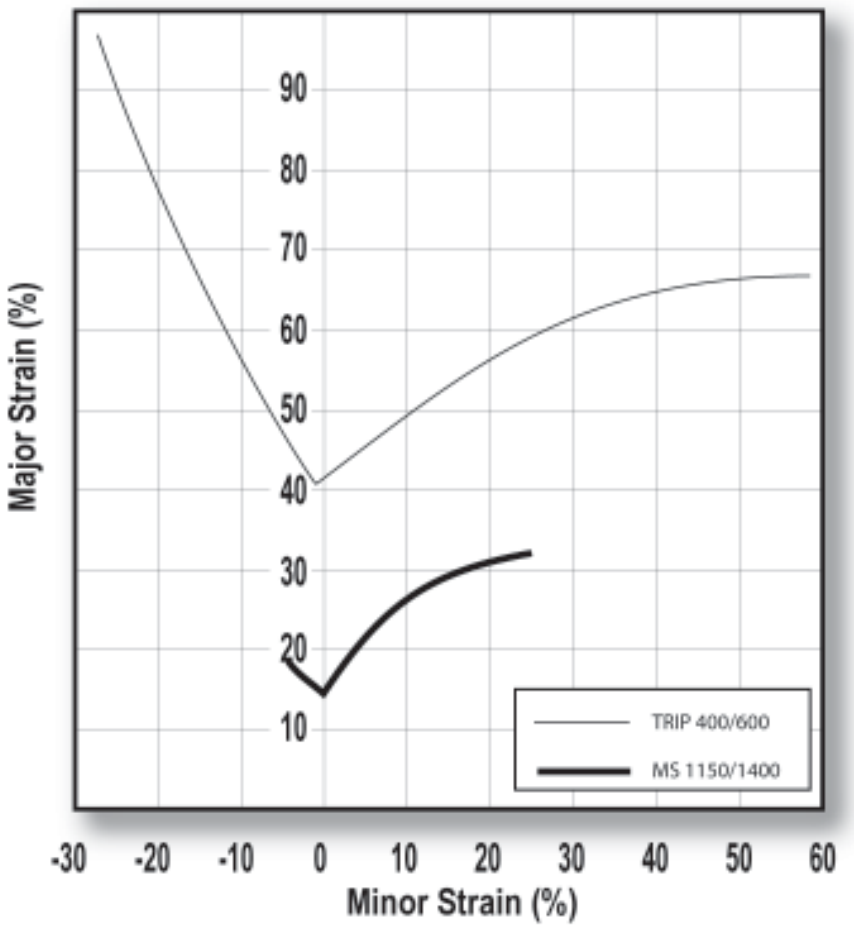


Figure 2-18 – Preliminary experimental FLCs for a t=1.2 mm TRIP steel and a t=1.5 mm MS steel.[K-1, C-1]

With only minor differences in sheet thickness, the height of the FLC_0 is primarily a function of the terminal work hardening exponent (n). The approximately constant n-value extending beyond the 10% strain range provides a measure of the terminal or high strain n-value.

The measured properties of the steels presented in Figures 2-17 and 2-18 are listed in Table 2-1.

Table 2-1 - Properties of steels in Figures 2-17 and 2-18.[K-1, C-1]

Grade	YS (MPa)	UTS (MPa)	Tot. El (%)	YPE (%)	Terminal n
Mild Steel 170/300	183	314	42.9	0	0.230
HSLA 350/450	377	443	28.4	2.8	0.170
DP 350/600	340	602	29.0	0	0.170
TRIP 400/600	393	631	34.0	0	0.230
MS 1150/1400	1356	1546	5.0	0	N.A.

Terminal n-values (except MS steel) are the average n measured between strain levels of 10% and uniform elongation.

Both HSLA 350/450 and DP 350/600 steels have terminal n-values (measured at high values of strain) equal to 0.17. Therefore, the FLC_0 values are equal as shown in Figure 2-17. These two steels have approximately the same YS and total elongations but the UTS values are very different. More interesting are the Mild 170/300 and TRIP 400/600 steels. Both have terminal n values of 0.23. However, the FLC_0 equation shown in Figure 2-17 currently cannot be applied to TRIP steels and must be further researched. The modified microstructures of the AHSS allow different property relationships to tailor each steel type and grade to specific application needs. Even more important is the requirement to obtain property data from the steel supplier for the types and grades being considered for specific applications.

2.C.2.b. Sheared Edge Stretching Limits

Extensive research work has been conducted in various parts of the world to study the capability of steel to withstand tensile stretching on sheared edges. This sheared edge can be created at many different times during the transition from steel mill to final assembly. These include coil slitting, blanking (straight and contour), offal trimming (external edges or internal cut-outs), hole punching, and other operations. Tensile stretching is most commonly created during hole expansion and stretch flanging. In terms of deformation mode, the edge simulates a tensile test with similar width and thickness reductions. The studies showed that the sheared edges had less stretchability compared to the rest of the stamping. The explanation was a reduction in the work hardening exponent or n-value of the edge metal due to cold work created during the cutting operation.

With the increased application of AHSS, stampings made from DP and TRIP steels showed yet another type of problem. Stretch flanging and hole expansion generated edge cracks at low strains – even for edges that had been milled to remove all of the cold work zone. The reduction in stretchability was evident in hole expansion tests. To understand the problem better, Table 2-2 describes the various forming modes and their formability limitations

Table 2-2 – Forming sequence for four different forming modes.

Increasing Deformation ↓

	A	B	C	D
Forming Sequence	Milled tension test samples	Conventional steels No sheared edges	Conventional steels Sheared edges	DP & TRIP steels Milled edges
Elastic deformation	●	●	●	●
Plastic deformation	●	●	●	●
Diffuse neck (width neck)	●			
Local elongation HET measurement (hole expansion test)				●
Cold worked cut edges Reduced n-value Reduced stretchability			●	
Local neck (through thickness neck) Predicted by FLC	●	●		
Failure – ductile	●	●	●	●

The tensile test (column A in Table 2-2) is the source for much of the mechanical property data. The milled edges of the tensile sample remove any cold worked zones that lead to early crack initiation. However, during the test a load maximum occurs due to work hardening becoming equal to geometrical softening. At this load maximum (UTS), a diffuse (width) neck localizes deformation within the neck and the remainder of the specimen terminates further deformation under the reducing load. Deformation continues in the diffuse neck until a local (narrow through thickness) neck initiates. All further deformation localizes in the local neck until ductile failure occurs.

Forming conventional steels into sheet metal stampings (column B) happens without the interference of a diffuse neck. Deformation continues until the onset of the local neck. The Forming Limit Curves discussed above in 2.C.2.a. predict the onset of the local neck.

The first loss of edge stretchability (column C) occurs when a sheared (cut) edge elongates because of an applied tensile stress. However, the metal in the sheared edge zone has experienced severe cold work. The shearing can create a work-hardened zone for a distance from the sheared edge equal to one-half metal thickness. The cold work reduces the work hardening capacity of the edge metal, lowers the n-value, and reduces the permissible edge stretch. The hole expansion test (HET) quantifies this reduction in edge stretchability. Figure 2-19.schematically shows the magnitude of the reduction in the hole expansion due to hole punching compared to a milled edge.

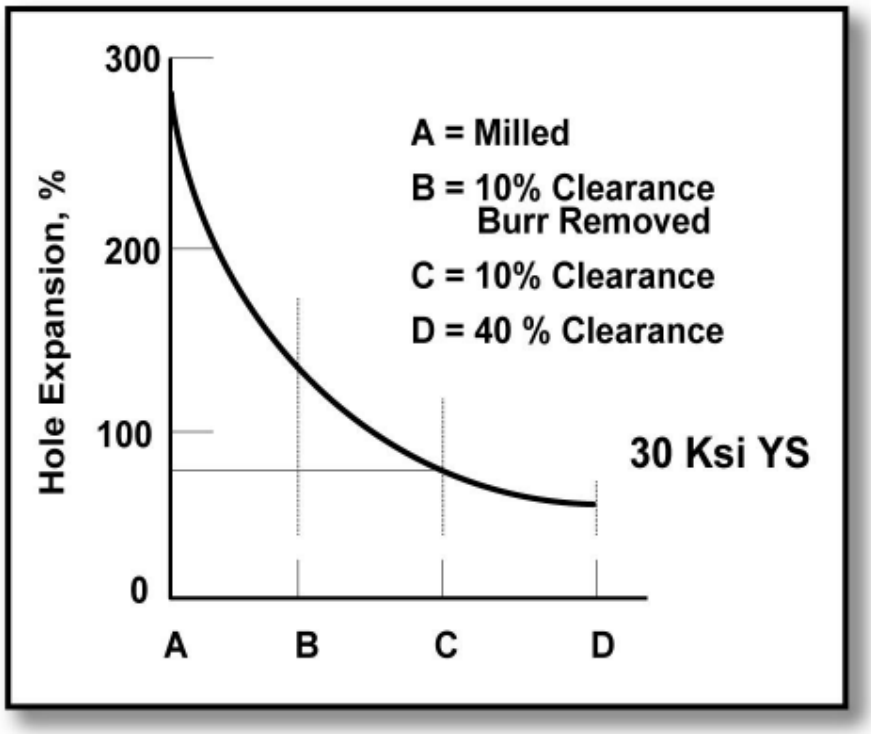


Figure 2-19 – Schematic showing the trend in percent hole expansion for 30 ksi Mild steel due to cold work during hole punching compared to a milled hole.[H-1]

Sheared edge stretchability is generally evaluated by two different hole expansion test methods. The first begins with clamping a flat blank containing a punched hole in the centre. A flat bottom punch with a diameter equal to the die opening is pushed into the blank. The circumference of the hole expands as the metal slides across the bottom of the punch. The second test begins with the clamping of the same flat blank with a punched hole in the centre. In this test, however, a conical punch is inserted into the hole. As the punch continues its travel, the circumference of the hole expands as a flange of increasing height is generated. When a variety of steels was tested by both methods, a correlation did exist between the two test methods. Either one could be used to compare edge stretching of different metals. However, the hole expansion test utilizing a conical punch has become the more common test because it is more simulative of a stretch flanging operation. The increase in hole diameter (or circumference) is given the symbol lambda (λ). The key to consistent data lies with the quality of the punched hole. Special efforts are needed to keep the tools sharp and damage free. Hard, wear resistant tools, preferably coated PM grade, are highly recommended. The hole expansion limits generated by a conical punch were consistently higher than the hole expansion tests created by a flat-bottom punch. Careful reproducibility of the sheared perimeter of the hole is required to run comparison tests on vastly different steels, such as AHSS and HSS. The same severe work hardening generated during the edge shearing prevents the use of traditional FLCs based on the as-received properties of the steel to determine allowable sheared edge stretching.

Research[V-1] similar to Figure 2-19 but devoted to AHSS and other HSS is presented in Figure 2-20. Note that the HE (%) can be significantly lower for punched holes compared to machined holes. This probably is due to the reduced local elongation of these multiphase steels, which can have interfacial shearing between the ductile ferrite matrix and the harder phases. A more detailed study of sheared edge stretching is available in reference K-6.

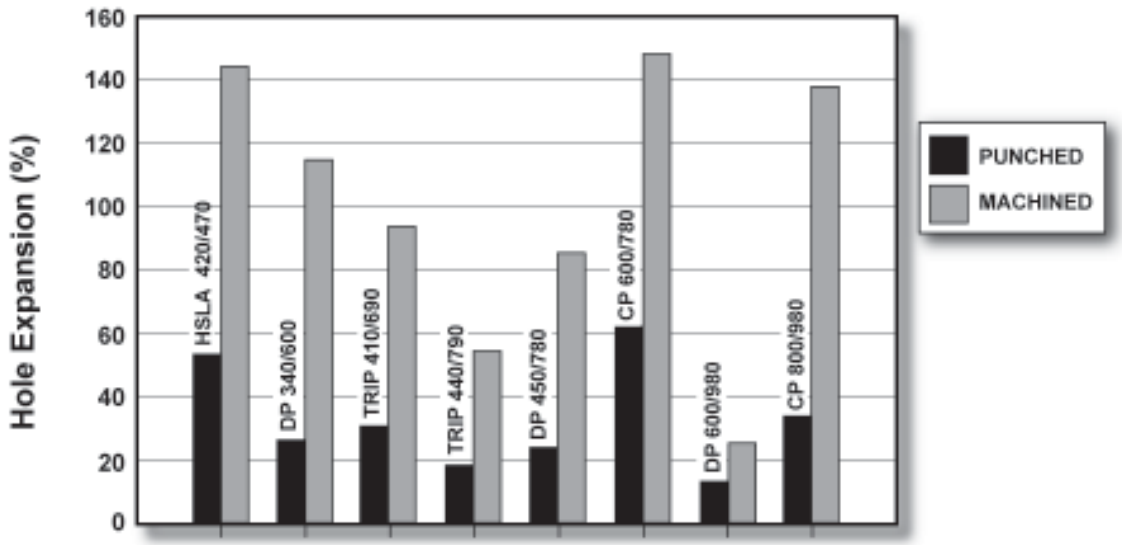


Figure 2-20 – Laboratory study shows the effect of damage (measured by a hole expansion test) done to sheet metal stretchability when a hole is punched in sheet metal compared to machining the hole.[V-1]

Production studies found the DP and TRIP steels had a unique type of edge stretch failure (column D in Table 2-2). These steels had early edge failure for edges pulled in tension. The cause was not cold working of the edges since milling removed all cold work. All these failures - as a group called “shear” failures - tentatively have been associated with the microstructure containing islands, bands, or other configurations of martensite. Extensive research is underway to determine the root cause of these failures.

Stretch flange and hole expansion forming operations for DP and TRIP steels are more complex than Table 2-2 shows. During production of parts from these steels, a reduced edge stretchability results from both the reduction in work hardening capacity due to the cold work of cutting (column C) and the ferrite-martensite microstructure common to both these steels (column D). The standard hole expansion test with a punched hole measures both these effects.

A different study[C-1] evaluated the hole expansion ratio created by hole punching tools as they wore in a production environment. The powder metallurgy (PM) tools had a 60 HRC. The tools were uncoated. Data in Figure 2-21 show the percent hole expansion from newly ground punches and dies (Sharp Tools) and from used production punches and dies (Worn Tools). The radial clearance was 0.1 mm. Only rust protection oil on the sheet was used during the punching. Aral Ropa oil was applied during the hole expansion. The poor edge condition after punching was caused by tool wear and possible microchipping. The clearance was hardly affected.

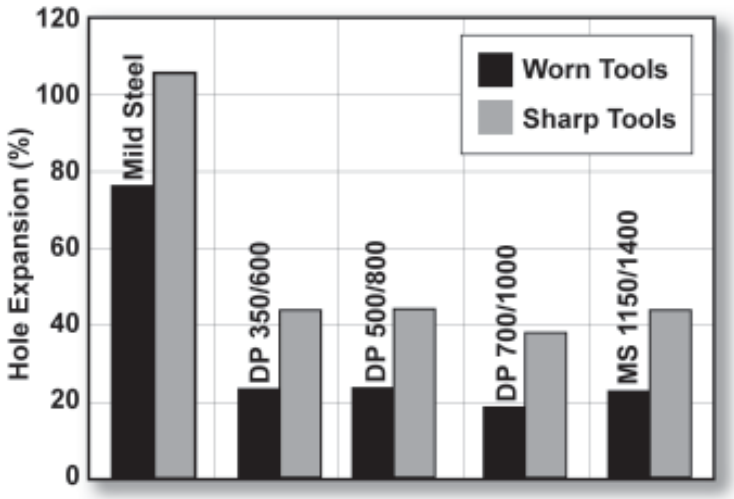


Figure 2-21 – Production tooling used to evaluate hole expansion tests using a conical punch with a 50 mm base diameter using sharp and worn tools.[C-1]

The conclusions from this study were: 1) When exposing a DP steel to edge deformation, make sure the best quality edge condition is utilized and the burr, if possible, should be facing inward, and 2) Use hard wearing tooling, preferably coated PM grades, for punching. Additional information on tool materials is available in 2.C.6.b.

Figure 2-21 shows the combination of cold work at the sheared edge and the effect of microstructure. If no cold work were present, a gradual decrease in HE (%) would be expected as the strength moves from the single phase Mild Steel to the single phase MS. However, the HE (%) drops dramatically for the DP 350/600 and then stays approximately constant for the DP 500/800 and DP 700/1000. This behaviour would be characteristic of the change in microstructure overriding the cold work effect.

To counteract this general trend of loss of edge stretching, properties of the AHSS can be further tailored to increase the sheared edge-stretching limit. AHSS gain their well-publicized improved total elongations from microstructures with unique differences in morphology, hardness, and amounts of low temperature transformation products (LTTPs). Unfortunately, these same microstructures reduce local elongations or local ductility (measured by λ) that affect hole expansion, stretch flanging, and bending. This problem is shown in Figure 2-22.

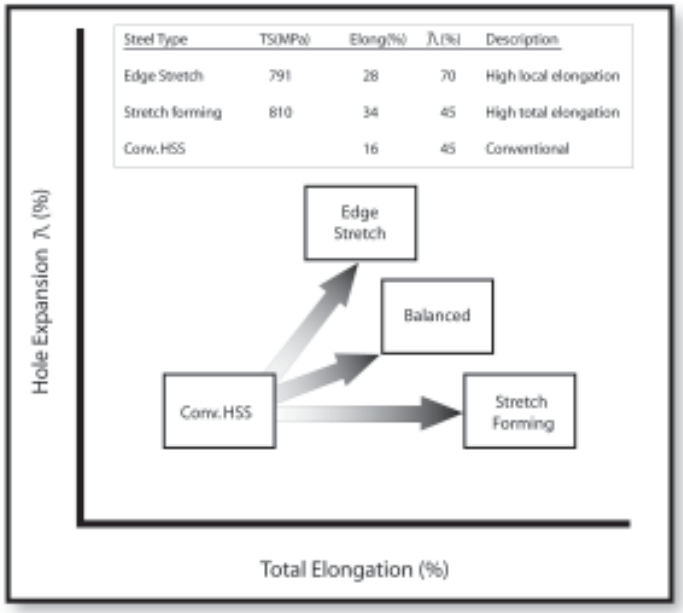


Figure 2-22 - Schematic showing AHSS tailored to high total elongation or high local elongation.[T-1]

The key to improved sheared edge stretchability is homogeneous microstructure. Such metallurgical trends include a single phase of bainite or multiple phases including bainite and removal of large particles of martensite. This trend is shown in Figure 2-23.

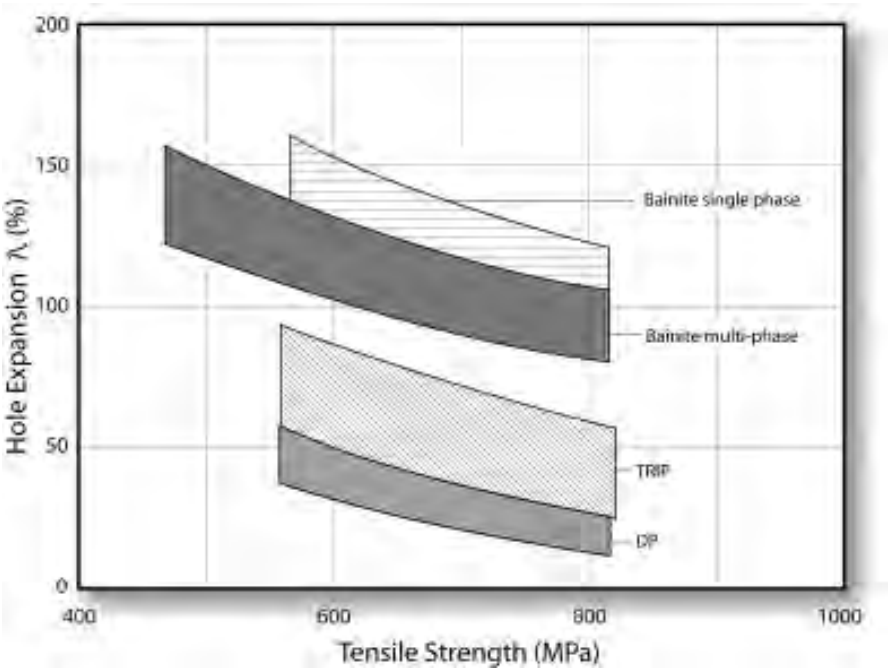


Figure 2-23 - Improvements in hole expansion by modification of microstructure.[N-1]

2.C.2.c. Shear Fracture

Automotive product designers utilize small radii for springback control, sectional stiffness, packaging constraints, and design features. Increased sensitivity to crack formation is observed for AHSS at small die radius to material thickness (R/t) ratios. Traditional forming limit curves or other press shop criteria do not predict these fractures. Likewise, usual forming simulations, such as computerized forming-process development, also do not flag these fractures. However, these shear fractures have occurred in die tryout.

Substantial research is underway to develop one or more tests that will predict the onset of these shear failures. Reference W-3 presents angular stretch-bend test results. Reference W-4 details pulling metal strips over radii with back tension. Most of the research results show significant reduction in available deformation for different grades of DP and TRIP steels. All the research focuses on finding a procedure that will predetermine at what level of strain specific steels will fail. This information then will be entered into Computerized Forming-Process Development analyses to determine feasibility of any given part design.

2.C.2.d. Key Points

Forming Limit Curves

- Differences in determination and interpretation of FLCs exist in different regions of the world. These Application Guidelines utilize one current system of commonly used FLCs positioned by FLC_0 determined by terminal n and t.
- This system of FLCs commonly used for low strength and conventional HSS is generally applicable to experimental FLCs obtained for DP steels.
- The left side of the FLC (negative minor strains) is in good agreement with experimental data for DP and TRIP steels. The left side depicts a constant thinning strain as a forming limit.
- Data for 1.2 mm steels shows the FLCs for HSLA 350/450 and DP 350/600 overlap.
- Determination of FLCs for TRIP, MS, TWIP, and other special steels present measurement and interpretation problems and need further development.

Sheared Edge Stretching Limits

- Sheared edge stretching limits are important for hole expansion and stretch flanging. All steels have reduced hole expansion limits caused by the cold work and reduced n-value of the metal adjacent to the cut edge.
- The hole expansion limits for milled edges of DP and TRIP steels suffer an additional reduction because of shear cracking associated with the interfaces between the ductile ferrite and the hard martensite phase in the microstructure. This reduction becomes more severe as the volume of martensite increases for increased strength.
- The microstructure of AHSS can be modified to enhance either total elongation for general stretch forming or local elongation for sheared edge stretching limits. The same microstructure generally does not provide high values for both total and local elongation values. However, some increases in both can be created to provide a balance of total and local elongation.

Shear Fractures

- Early shear type fractures have been encountered without a sheared edge when a small tool radius to sheet thickness (r/t ratio) is encountered within a stamping.
- Shear fractures are not predicted by the forming limit curve or computerized forming-process development.
- A number of research programs are attempting to develop a new bending test that will quantify when these failures will occur in any specific sheet metal.

2.C.3. Forming Modes

Part designers are interested in the forming capabilities of the steels they specify. This is true of HSS and even more so for AHSS. Unfortunately, complex stampings are composed of several different basic forming modes, which react to a different set of mechanical properties. Likewise, formability of steel, and especially AHSS, cannot be characterized by a single number. Therefore, formability comparisons of AHSS to conventional HSS must be done for each basic forming mode. In this section, three general groups (stretching, cup drawing, bending/roll forming) are reviewed.

2.C.3.a. Stretching

As a rule, the depth of a part by stretching increases as the work hardening exponent (n) increases. As discussed in 2.C.1.c., an increase in n value can increase:

1) The allowable stretch as determined by the forming limit curve (FLC).
2) The ability of steel to distribute the strain distribution more uniformly in the presence of a stress gradient.

DP steels have an increased n value at low values of strain compared to HSS (Figure 2-6). Therefore, DP steels have increased tendency to flatten strain gradients at their inception. Part designers can benefit from AHSS for all stamping areas that are formed in pure stretch, such as embossments, character lines, and other design features with localized strain gradients (Figure 2-24). Peak strain reduction in these gradients also means less localized thinning for in-service requirements.

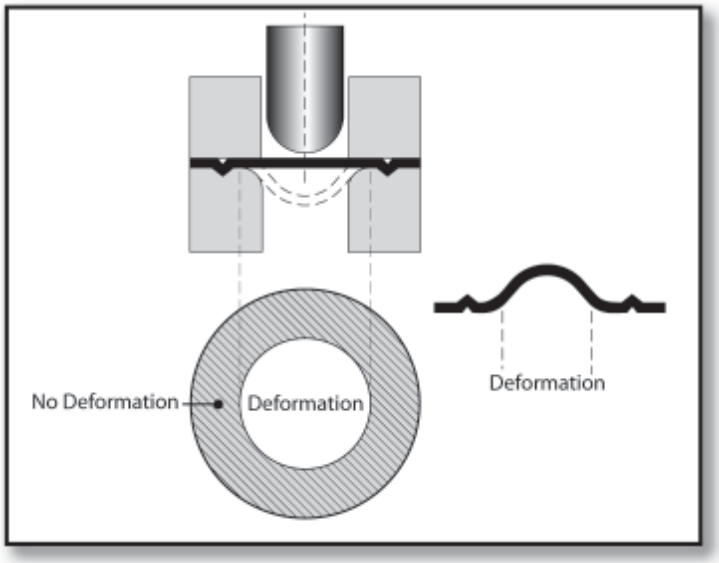


Figure 2-24 - Stretch forming generated by a rounded or flat bottom punch.

By 8% strain, the higher instantaneous n value of DP steels has been depleted (Figure 2-6) and the n values are similar to conventional HSS. Therefore, traditional formulas used to set the height of the FLC used for HSLA can be used for DP steels when compared at equal yield strengths (Figure 2-17). However, when comparisons are made between DP and HSLA steels with equal tensile strengths, the DP steels do have higher FLCs. Caution must be taken when those stretch operations (embossments and other design features) are performed on prior-deformed areas. Due to the rapid work hardening rate for AHSS, the residual formability from the prior operation may be quite different from that for conventional HSS.

TRIP steels have high n values compared to HSS throughout their entire strain range (Figure 2-8). A continual high n means steel is much more suitable to suppress localization of strain generated by design features in the stamping. The higher terminal (high strain) n value also means a higher FLC (Figure 2-18), where, for example, the FLC for the TRIP 350/600 steel approximates that of a Mild steel.

In stretch forming, the TRIP steel has an additional advantage compared to DP and conventional HSLA steels. As the strain begins to localize at the high stress locations in the stamping, the deformation causes additional transformation from retained austenite to martensite. This further strengthens the deformation zone and forces redistribution of deformation to areas of less strain.

The total effect of the higher n value and additional transformation to martensite is documented by the Limiting Dome Height (LDH) test results shown in Figure 2-25.[N-1] The actual properties of the two steels tested are:

TRIP 399/614, uniform elongation = 26.3%, total elongation = 35.3%
HSLA 413/564, uniform elongation = 16.9%, total elongation = 27.5%

Blanks were coated with conventional anti-rust oil and held with a circular lock bead of 165 mm diameter. The minimum hemispherical dome height at failure is substantially higher for the TRIP steel compared to the equivalent HSLA steel.

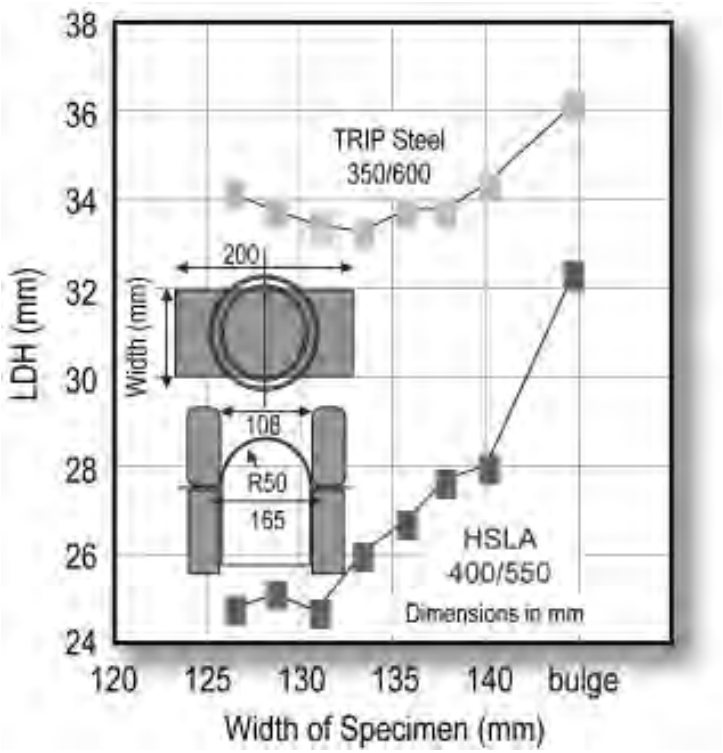


Figure 2-25 - Limiting Dome Height is greater for TRIP than HSLA for the two steel grades tested.[T-2]

The Limit Dome Height test results for EDDQ (vacuum-degassed Interstitial-free) steel and three AHSS are in Figure 2-26. Instead of plotting the various dome heights (as in Figure 2-25) to find the minimum value, Figure 2-26 simply shows the minimum value for each steel. Note that the TWIP 450/1000 has greater stretchability than the low strength IF steel (EDDQ).

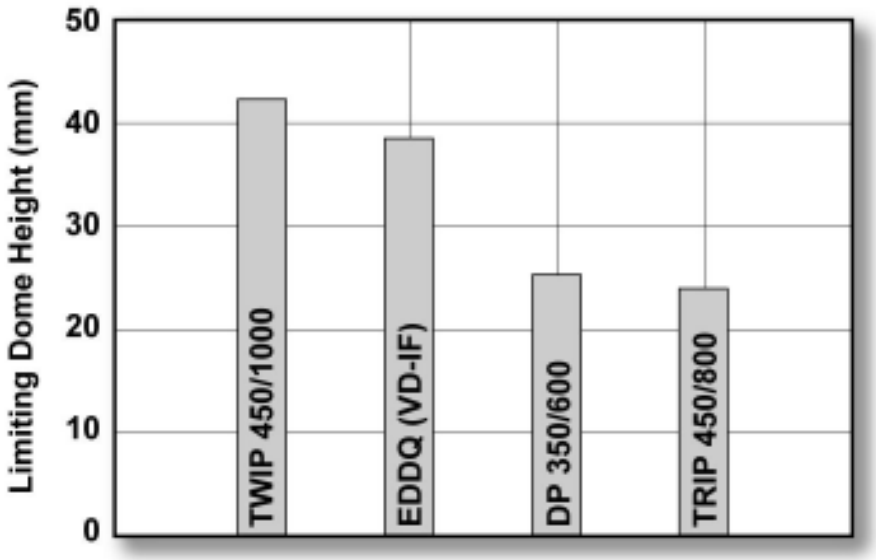


Figure 2-26 – Liming Dome Height values reflect relative stretchability of three AHSS compared to a low strength IF steel.[P-2]

The same tooling, steels, and lubricant from Figure 2-25 generated the thinning strains in Figure 2-27. However, the 50 mm radius hemispherical punch stretched the dome height to only 25 mm for both steels. The increased capability of the TRIP steel to minimize localized thinning is observed.

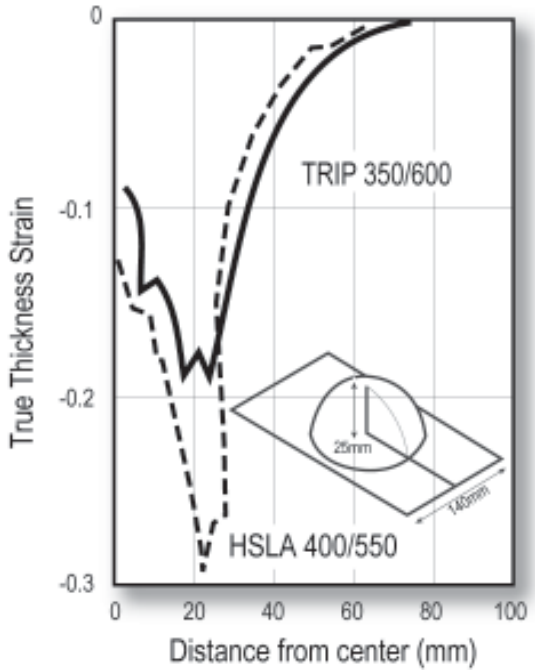


Figure 2-27 - The local thinning is smaller for TRIP than HSLA at a constant dome height.[T-2]

A series of hemispherical dome stretch forming tests showed the expected decrease in stretchability as the yield and tensile strength increased (Figure 2-28).

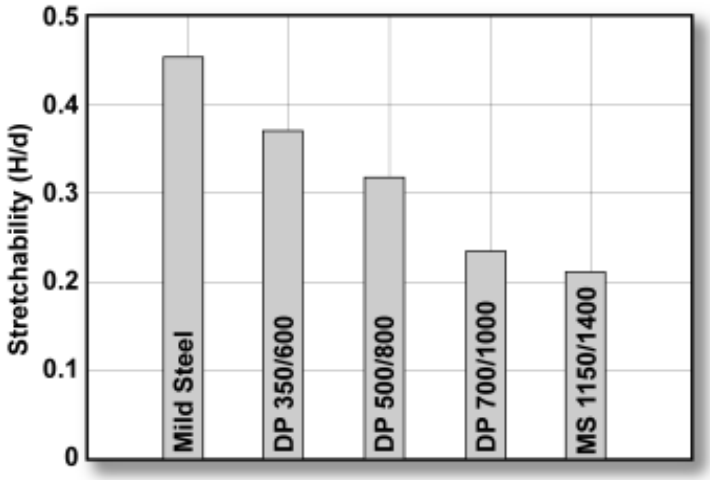


Figure 2-28 - Dome stretch tests using a 100 mm hemispherical punch and a clamped blank. Sheet thickness is 1.2 mm except for the MS thickness of 1.5 mm.[C-1]

The maximum length of line that can be stretched depends on tool design, lubrication, and many other inputs to the forming system. Computerized forming-process development is an important procedure for assessing the benefits of AHSS over conventional HSS for specific stamping designs.

2.C.3.b. Deep Drawing (Cup Drawing)

Deep drawing is defined as radial drawing or cup drawing (Figure 2-29). The flange of a circular blank is subjected to a radial tension and a circumferential compression as the flange moves in a radial direction towards the circular die radius in response to a pull generated by a flat bottom punch. In addition to forming cylindrical cups, segments of a deep drawn cup are found in corners of box-shaped stampings and at the ends of closed channels.

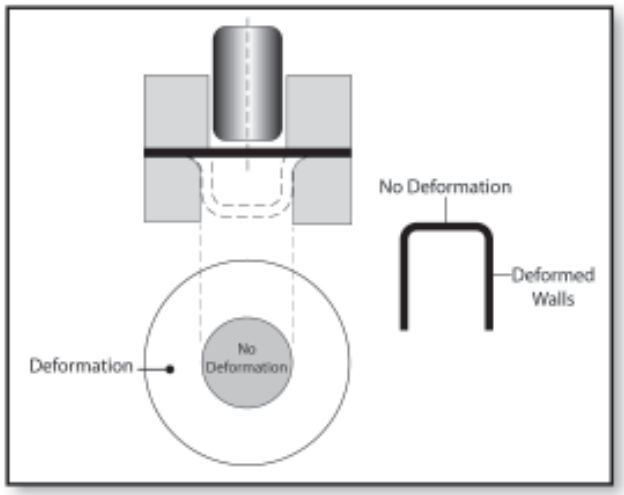


Figure 2-29 - A circular blank is formed into a cylindrical cup by the deep drawing, radial drawing, or cup drawing method of deformation.

The steel property that improves cup drawing or radial drawing is the normal anisotropy or r_m value. Values greater than one allow an increase in the limiting draw ratio (LDR), which is the maximum ratio of blank diameter to punch diameter allowed in the first draw. In contrast, the LDR is insensitive to the strength of the steel and the n value.

High-strength steels with UTS greater than 450 MPa and hot-rolled steels have r_m values approximating one and the LDR averages around 2. Therefore, DP steels have an LDR similar to HSS. However, the TRIP steels have a slightly improved LDR deep drawability.[T-2] Since the martensite transformation is influenced by the deformation mode (Figure 2-30), the amount of transformed martensite generated by shrink flanging in the flange area is less than the plane strain deformation in the cup wall. This difference in transformation from retained austenite to martensite makes the wall area stronger than the flange area, thereby increasing the LDR.

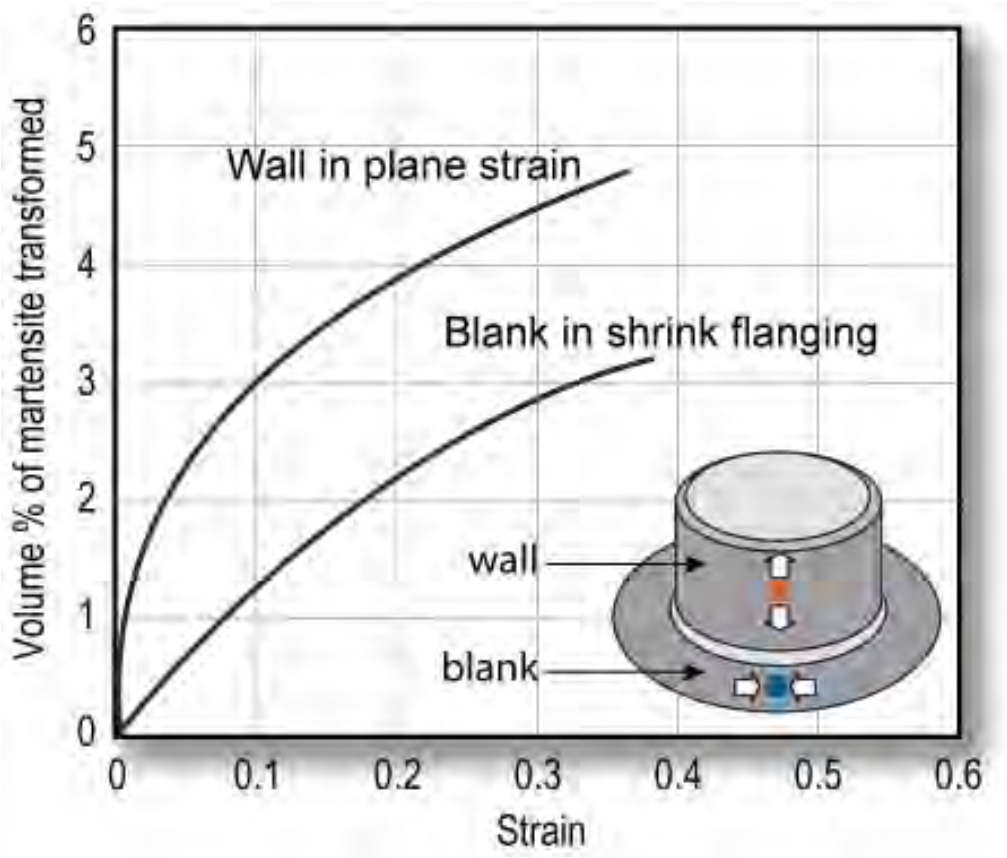


Figure 2-30 - The cup wall is strengthened more than the flange due to increased amounts of transformed martensite in TRIP steels.[T-2]

Excluding the special cup drawing features of the TRIP steels mentioned above, laboratory cup drawing experiments show an approximate LDR of 2 for the DP steels tested (Figure 2-31).

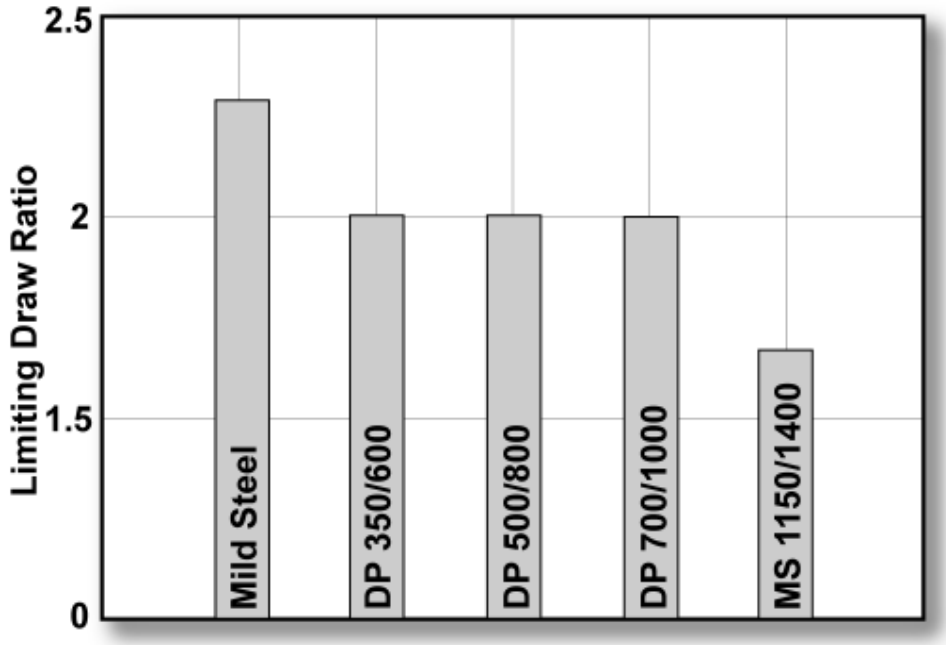


Figure 2-31 - LDR tests for Mild, DP, and MS steels.[C-1]

The absolute value of the LDR, however, also depends on the lubrication, blank holder load, die radius, and other system inputs.

2.C.3.c. Bending

The usual mode of bending is curvature around a straight line radius (Figure 2-32). Across the radius is a gradient of strains from maximum outer fibre tension though a neutral axis to inner fibre compression. No strain (plane strain) occurs along the bend axis.

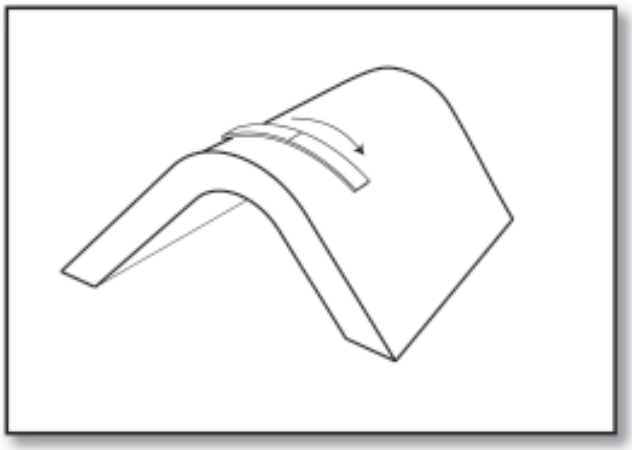


Figure 2-32 - Typical three-point bend has outer fibre tension and inner fibre compression with a neutral axis in the centre.

Three-point Bending

A higher total elongation helps sustain a larger outer fibre stretch of the bend before surface fracture, thereby permitting a smaller bend radius. Since total elongation decreases with increasing strength for a given sheet thickness, the achievable minimum design bend radius must be increased (Figure 2-33).

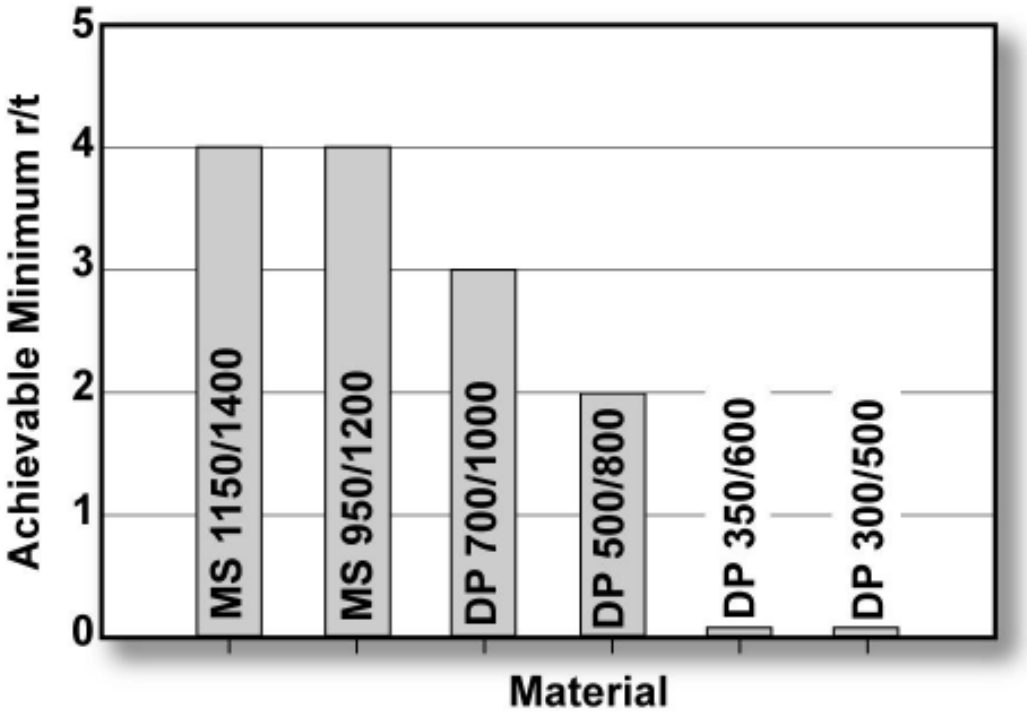


Figure 2-33 – Achievable minimum bend radius (r/t) in a three-point bend test increases as the total elongation of the steel decreases.[S-5]

For equal strengths, most AHSS have greater total elongations than HSS (Figures 2-2 and 2-3). The microstructure of DP and TRIP consists of a highly inhomogeneous combination of soft ferrite matrix and hard martensite islands. This microstructure creates a larger total elongation due to the increased work hardening. A smaller minimum design bend radius is expected. However, the deformation can localize around the hard phases and create low local elongations or edge stretch capability as measured by the hole expansion test (Figure 2-20). Several cases of early radii cracking of production bending DP and TRIP steels have been attributed to this lower local elongation.

2.C.3.d. Roll Forming

The roll forming process forms a flat metal strip by successive bending into the desired shape. Each bending operation can be distributed along several sets of rolls to minimize strain localization and compensate for springback. Therefore, roll forming is well suited for generating many complex shapes from AHSS, especially those with low total elongations such as MS.

Roll forming can produce AHSS parts with:

- Steels of all levels of mechanical properties and different microstructures.
- Springback compensation without particularly complex tools.
- Small radii depending on the thickness and mechanical properties of the steel.
- Reduced number of forming stations compared with lower strength steel.

However, the forces on the rollers and frames are higher. A rule of thumb says that the force is linear with the strength but square with the thickness. Therefore, structural strength ratings of the roll forming equipment must be checked in order to avoid bending of the shafts.

Typical values of the minimum radius and springback can be determined for the different AHSS with tests on simple U shapes performed with six stations (Figure 2-34)

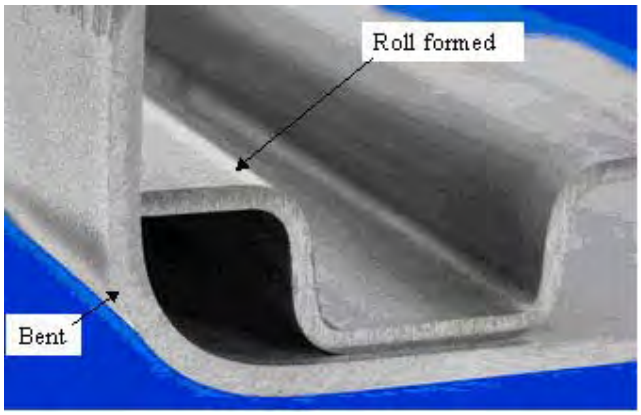


Figure 2-34 - Comparison between the minimum radii made by roll forming and bending a 2 mm MS 1050/1400 steel.[S-5]

The value of minimum internal radius of a roll formed component depends primarily on the thickness and the tensile strength of the steel (Figure 2-35). Roll forming allows smaller radii than a bending process.

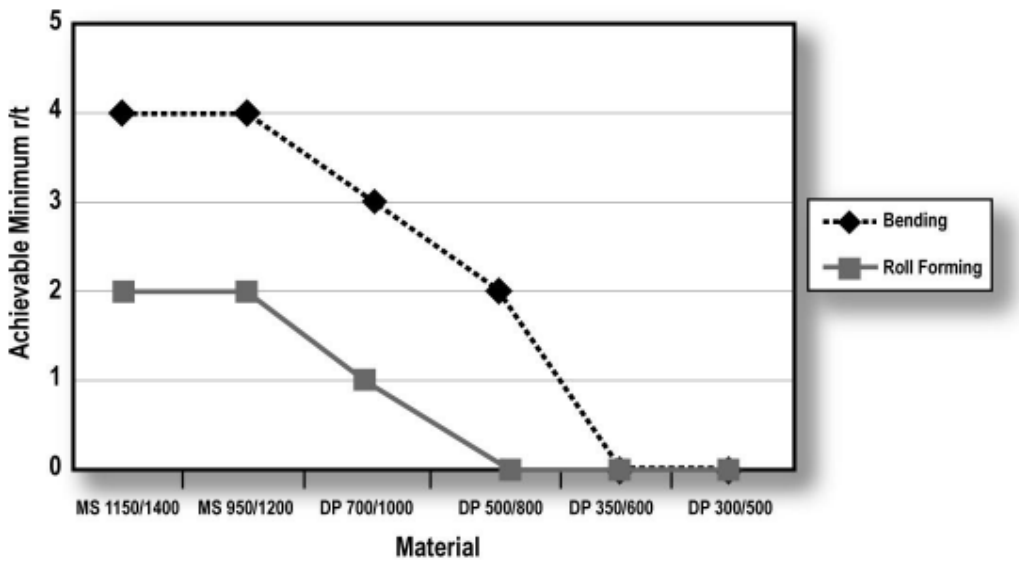


Figure 2-35 – Achievable minimum r/t values for bending and roll forming for different strength and types of steel. [S-5]

The main parameters having an influence on the springback are the radius of the component, the thickness, and the yield strength of the steel. The effects of these parameters are shown in Figure 2-36. As expected, angular change increases for increased tensile strength and bend radius.

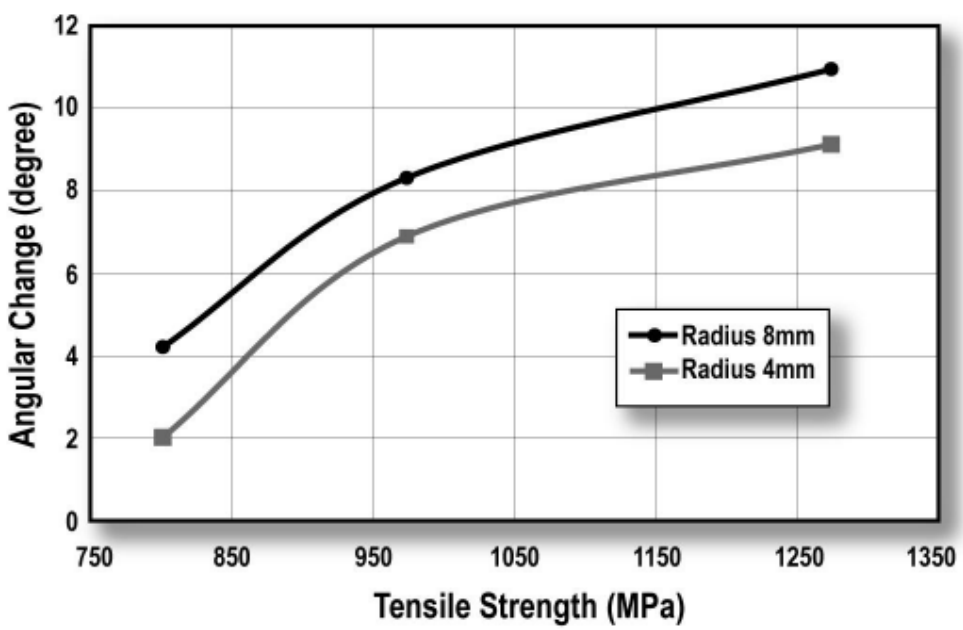


Figure 2-36 – Angular change increases with increasing tensile strength and bend radii. [A-4,]

Roll forming makes it possible to control the strains in the bend to minimise the springback (Figure 2-37).

Figure 2-37- A profile made with the same tool setup for three steels having different strengths and the same thickness. Even with the large difference in strength, the springback is almost the same. [S-5]

2.C.3.e. Hot-Forming

Today, many product designs tend to combine maximum complexity and part consolidation with the highest possible final strength steel required for in-service applications. Maximum part complexity usually requires superior stretchability as evidenced by high work hardening capability and defined by the n-value. Part consolidation might take three non-severe parts and make one very severe large part. Imagine three separate parts deep drawn with extensive metal flow from the binder to provide maximum part depth. Laying the three parts side-by-side in a straight line, now connect them with welds to make the final part. Now attempt to make all three attached parts from a single blank in one die. There is no binder area to feed the centre part, which now must form completely by excessive stretch forming. Making the problem worse, increasing the strength of the as-received steel reduces the stretch capacity of the steel because the work hardening exponent (n-value) decreases with increasing strength for each type of steel. Finally, springback problems increase as the yield strength increases.

The hot-forming process can minimize all the above problems. The following steps present details of the hot-forming process.[M-2, I-1] While several steels are applicable, the data below represent the most common boron-manganese AHSS. The initial microstructure is composed of ferrite and pearlite.

Direct Hot-forming Process

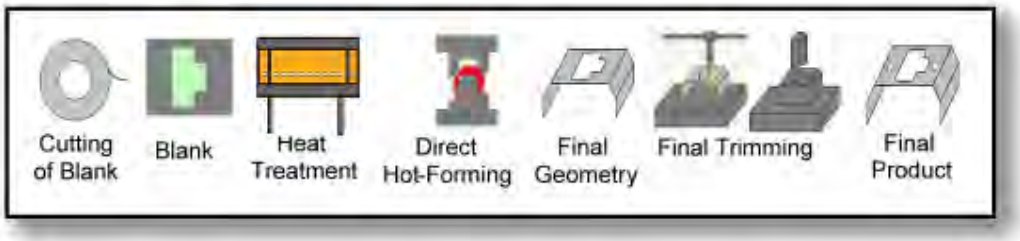


Figure 2–38A – Schematic showing steps in the Direct Hot-Forming process. [V-2]

Step 1 – Cut the blank. The as-received HF steel is at room temperature with yield strength of 350-400 MPa, a tensile strength of 550-600 MPa, and a total elongation around 25% (See true stress-strain curves in Figure 2-10). Blanking dies must withstand these properties.

Step 2- Heat the blank: The target temperature is above 900 ºC needed to change the microstructure to austenite. Typical furnace time is 5-8 minutes. Because of the high temperature heating, uncoated steel would generate a surface oxide. Currently, an aluminium-silicon coating prevents the formation of this surface oxide. The coating also helps prevent in-service corrosion in part areas difficult to shot blast or otherwise remove the surface oxide prior to application of additional corrosion protection treatments.

Step 3 – Transfer blank to die: Robots can transfer the blank to the water-cooled die in about three seconds.

Step 4 – Forming the part: Forming temperate typically starts at 850 ºC and ends at 650 ºC. While in the austenitic range, the true yield stress is relatively constant at 40 MPa with high elongations greater than 50%. This permits parts with maximum complexity and part consolidation to form successfully.

Step 5 – In-die quenching: When forming is completed, the part now contacts both the punch and die for both side quenching. The minimum quench rate is 50 ºC/sec. Some actual cooling rates are two or three times the minimum rate. The quench process transforms the austenite to martensite throughout the entire part. The room temperature properties of the part are 1000-1250 MPa yield strength, 1400 -1700 tensile strength, and 4-8% elongations (See the true stress-strain curve in Figure 2-10). Total time for robot transfer, forming, and quenching is about 20-30 seconds. With smaller parts, forming and quenching of multiple parts in the die reduces per part processing time.

Step 6 – Post-forming operations: The very high strength and low elongations of the final part restrict these final operations. The room temperature part should not undergo additional forming. Any special cutting, trimming, and piercing equipment must withstand the high loads generated during these operations.

Indirect Hot-forming Process

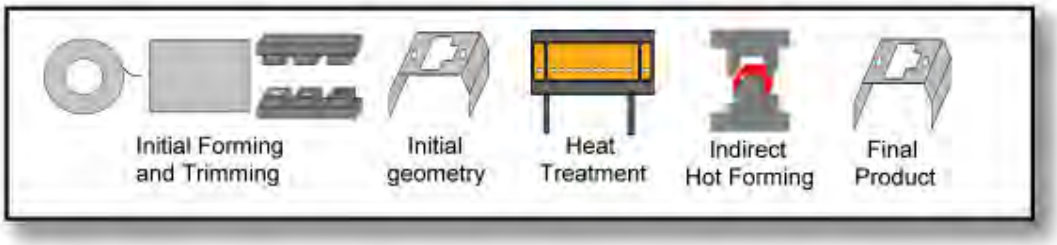


Figure 2-38B – Schematic showing steps in the In-Direct Hot-Forming process. [V-2]

The indirect hot-forming process adds a preform step between Step 1 - Cut the blank and Step 2 – Heat the blank in the direct hot-forming process described above. Here, preforming most of the part geometry at room temperature occurs without generating failures based on incoming steel properties. This room temperature forming in a traditional die aims for 90-95% of the final part shape. The part is trimmed and then subjected to the usual heating cycle in Step 2 above. Additional hot-forming is now possible for areas of the part too severe to form at room temperature. However, the in-direct forming process has a cost increase over the direct hot-forming process – two dies are required instead of one.

Benefits

1. Part has low directionality of properties measured by r-value anisotropy.
2. Springback issues eliminated, which is remarkable considering the extremely high final part strength.
3. Manufactured parts have low distortion.
4. Part consolidation has high feasibility for success.
5. Both high yield strength and steep cyclic stress-strain response create excellent fatigue performance.
6. Very high strength resists part deformation.
7. A 10% increase in yield strength (about 100 MPa) bake hardening effect can further increase in-service strength.
8. Hot-forming has the highest potential for weight reduction of crash components.

2.C.3.f. Key Points

Stretching

- DP steel has a higher initial n value than TRIP steel, which helps flatten emerging strain gradients and localized thinning. Stretch form features such as embossments can be slightly sharper or deeper. DP steel does not have a higher FLC compared to HSS with comparable YS.
- TRIP steels benefit from a higher n throughout the deformation process, which helps to flatten emerging strain gradients and reduce localized thinning. In addition, the height of the FLC is increased and higher values of strain are allowed before failure.
- The limited stretchability of both HSS and AHSS (compared to Mild steels) increases the importance of product design, change of forming mode, utilization of a preform stage, lubricant selection, and other process design options.

Deep Drawing (Cup Drawing)

- The LDR for both HSS and DP steels is approximately two because the r_m values for most HSS and AHSS are approximately one.
- The LDR for TRIP steel is slightly greater than two because transformation strengthening in the cup wall is greater than equivalent strengthening in the deforming flange.

Bending

- Since total elongation decreases with increasing strength for a given sheet thickness, the minimum design bend radius must be increased.
- For equal strengths, most AHSS have greater total elongations than HSS.
- Roll forming can produce AHSS parts with steels of all levels of mechanical properties and different microstructures.
- Roll forming creates springback compensation primarily though overbending without particularly complex tools.

Hot forming

- For Direct hot-forming, the sheet steel is heated to approximately 900 ºC.
- The yield stress during deformation is about 40 MPa.
- The part is quenched to achieve a martensitic microstructure with a very high yield and tensile strength.
- The formed and quenched part has no springback issues.
- For In-Direct hot forming, most of the part shape is formed at room temperature prior to the heating and quenching cycle.

2.C.4. Tool Design

The primary concerns for tool design for forming AHSS are:

1) Increased forces required to form the sheet metal.
2) Need for additional tool features for increased springback compensation.

2.C.4.a. Tool Materials

In general, the existing tool and die shop procedures to select the appropriate die material can be used to select dies made to stamp AHSS grades. However, the considerably higher strength level of these grades exerts proportionally increased load on the die material. AHSS might reach hardness values 4-5 times higher than Mild steel grades. This is partially due to the microstructure of the sheet metal itself since some grades include martensitic phases for the required strength. For the martensitic grades (MS), the basic structure is martensite with tensile strengths approaching 1700 MPa.

The higher forces required to form AHSS require increased attention to tool specifications. The three primary areas are:

- Stiffness and toughness of the tool substrate for failure protection.
- Harder tool surface finishes for wear protection.
- Surface roughness of the tool.

Lifetime and performance of a particular drawing die is primarily determined by the accepted amount of wear/galling between maintenance periods. When selecting die material, some of the key elements that affect the specification of the die material are:

- Sheet metal: strength, thickness, surface coating.
- Die construction, machineability, radii sharpness, surface finish.
- Lubrication.
- Cost per part.

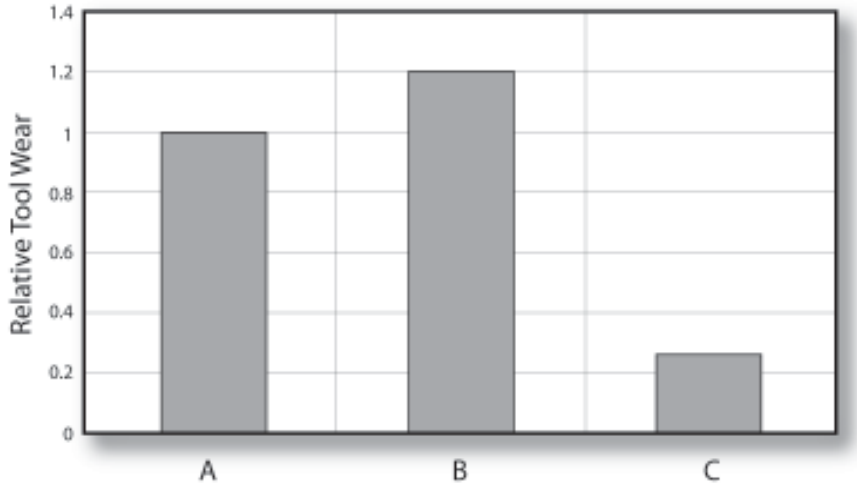
AHSS characteristics must be determined when designing tools. First is the initial, as-received yield strength, which is the minimum yield strength throughout the entire sheet. Second is the increase in strength level, which can be substantial for stampings that undergo high strain levels. These two factors acting in tandem can greatly increase the local load. This local load increase mostly accelerates the wear of draw radii with a less pronounced effect on other surfaces.

Counteracting this load increase can be a reduction in sheet thickness. Thickness reduction for weight saving is one primary reason for applications of AHSS. Unfortunately, the reduced thickness of the steel increases the tendency to wrinkle. Higher blankholder loads are required to suppress these wrinkles. Any formation of wrinkles will increase the local load and accelerate the wear effects.

Tool steel inserts for forming dies must be selected according to the work material and the severity of the forming. Surface coatings are recommended for DP 350/600 and higher grades. When coatings are used, it is important that the substrate has sufficient hardness/strength to avoid plastic deformation of the tool surface - even locally. Therefore, a separate surface hardening, such as nitriding, can be used before the coating is applied. Before coating, it is important to use the tool as a pre-production tool to allow the tool to set, and to provide time for tool to adjust. Surface roughness must be as low as possible before coating. R_a values below 0.2 mm are recommended. Steel inserts of 1.2379 or 1.2382 with a TiC/TiN coating are recommended for local high-pressure die areas wearing the zinc off galvanized blanks.

Tool steels for cutting, trimming, and punching tools must be selected in a similar way. Tool hardness between 58 and 62 HRC is recommended. Coatings may be used to reduce tool wear, but for the highest strength steels (above 1000 MPa tensile strength) use of coatings only generates limited further improvements. At this level of steel strength, coating failures occur due to local deformation of the die material substrate. Heat-treated (hardened) cutter knives of 1.2379 or 1.2383 show minor wear of the cutter edge. The radial shear gap should be around 10% of the blank thickness.

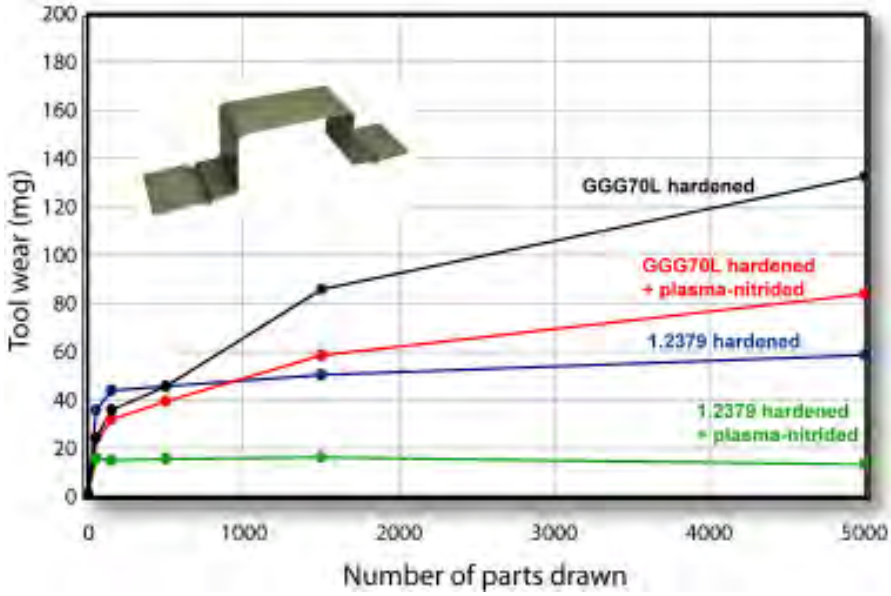
High performance tool steels, such as powder metallurgy (PM) grades, are almost always economical, despite their higher price, because of their low wear rate. Figure 2-39 shows the relative tool wear when punching Mild steel with conventional tool steel (A) and punching of DP 350/600 with an uncoated (B) and coated (C) PM tool steel.



A = Mild steel formed with 1.2363 tool steel dies (X100CrMoV5/1; US A2; Japan SKD 12)
B = DP 350/600 steel formed with 1.3344 tool steel dies (carbon 1.20%, vanadium 3%)
C = DP 350/600 steel formed with 1.3344 tool steel dies + hard surface CVD

Figure 2-39 - Tool wear results for different tool steels and surface treatments using Mild steel with A2 dies (A) for a reference of 1.[H-2] Tests B and C show tool wear for DP 350/600 formed in uncoated (B) and coated (C) PM dies.

Research on different surface treatments for a hat-profile drawing with draw beads showed a similar effect of coated surfaces on a cast iron die and a tool steel die (Figure 2-40).



GGG70L = Spheroid graphite bearing cast iron, flame hardened
1.2379 = Tool steel (X155CrMo12/1; US D2; Japan SKD 11)

Figure 2-40 - Surface treatment effects on tool wear, DP steel EG, 1mm.[T-3]

Ceramic tool inserts have extreme hardness for wear resistance, high heat resistance, and optimum tribological behaviour, but have poor machineability and severe brittleness. High costs are offset by reduced maintenance and increased productivity. While not commonly used, the ceramic tool inserts offer a possible solution to high interface loading and wear.

Additional information on tool wear is contained in Section 2.C.6.b. Tool Wear, Clearances, and Burr Height.

2.C.4.b. Tool Design Issues

Goals for springback compensation:

- Design out springback in the first draw stage to eliminate additional costly corrective operations.
- Consider strain path and reduce the number of bend/unbend scenarios.
- Adequate strain levels in the panel must be achieved to avoid greater springback and sidewall curl.
- Higher press forces are experienced on the structure of the tool.

Concerns for trim and pierce tool design:

- Engineer trim tools to withstand higher loads since AHSS have higher tensile strength than conventional high-strength steels.
- Proper support for the trim stock during trim operation is very important to minimize edge cracking.
- Modify trim schedule to minimize elastic recovery.
- Shedding of scrap can be a problem because springback of DP steel can cause scrap to stick very firmly in the tool.

Flange design:

- Design more formable flanges to reduce need for extra re-strike operations.
- Areas to be flanged should have a “break-line” or initial bend radius drawn in the first die to reduce springback.
- Adapt die radii for material strength and blank thickness.

Draw beads:

- Draw beads can generate large amount work hardening and increased press loads.
- Utilize draw beads to induce strain and therefore reduce elastic recovery.
- Optimize the use of shape and size of blanks to reduce the reliance on draw beads, which can excessively work harden the material before entering the die opening.

Guidelines to avoid edge cracking during stretch flanging:

- Abrupt changes in flange length cause local stress raisers leading to edge cracks. Hence, the transition of flange length should be gradual.
- Use metal gainers in the draw die or in the die prior to stretch flange operation to compensate for change in length of line that occurs. This can avoid edge cracking of a stretch flange.
- Avoid the use of sharp notch features in curved flanges.
- Edge preparation (quality of cut) is a critical factor.

Correcting loose metal:

- The higher strength of AHSS makes it more difficult to pull out loose metal or achieve a minimum stretch in flat sections of stampings.
- Increase the use of addendum, metal gainers (Figure 2-41), and other tool features to balance lengths of line or to locally increase stretch.

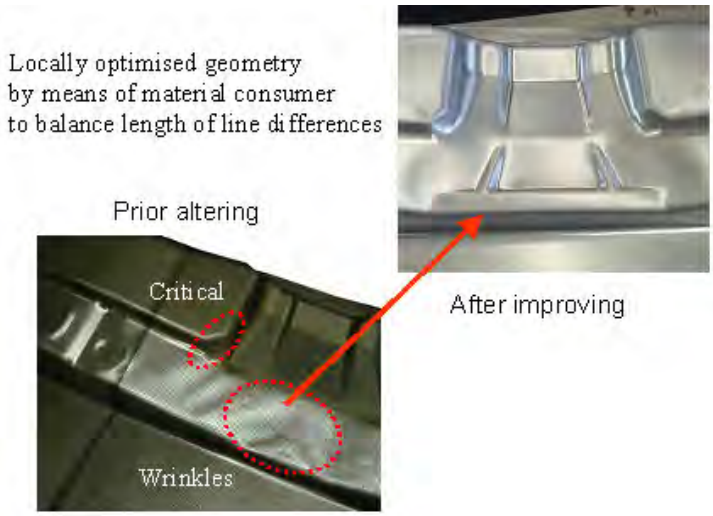


Figure 2-41 - Insertion of metal gainers to avoid insufficient stretched areas and eliminate buckles.[T-3]

2.C.4.c. Prototype Tools

For prototyping tools, normally soft tool materials are used and tool surfaces are not protected by wear resistant coatings during tool try out. When laser cut blanks of AHSS are used during try out, the blank holder surface may be damaged due to the high hardness in the laser cut edges.

Measures to be taken:

- Close control of laser cutting parameters in order to reduce burr and hardness.
- Deburr the laser cut blanks.

Soft tools may be used for manufacturing prototype parts and the inserts used to eliminate local wrinkles or buckles. However, soft tools should not be used to assess manufacturability and springback of AHSS parts.

2.C.4.d. Key Points

- Areas of concern are the higher working loads that require better tool materials and coatings for both failure protection and wear protection.
- The higher initial yield strengths of AHSS, plus the increased work hardening of DP and TRIP steels can increase the working loads of these steels by a factor 3 or 4 compared to Mild steels.
- AHSS hardness values might increase by a factor 4 or 5 over those of Mild steel.
- Powder metallurgy (PM) tools may be recommended for some AHSS applications.
- Parameters for normal tool design will have to be modified to incorporate more aggressive springback compensation techniques.
- Design process to minimize wrinkling. Wrinkling leads to higher loads and more tool wear.

2.C.5. Springback

Decades ago, the major concern in sheet metal forming was elimination of necks and tears. These forming problems were a function of plastic strain and generally were addressed by maintaining strain levels in the part below specific critical strains. These critical strains were dictated by various forming limits, which included forming limit diagrams, sheared edge stretch tests, and in-service structural requirements.

Today the primary emphasis has shifted to accuracy and consistency of product dimensions. These dimensional problems are a function of the elastic stresses created during the forming of the part and the relief of these stresses, or lack thereof, during the unloading of part after each forming operation. These dimensional problems or springback are created in all parts. However, their magnitude generally increases as the strength of the steel increases. Many companies have attacked springback problems with proprietary in-house compensation procedures developed over years of trial and error production of various parts. An example would be specific over-crowning of a hood panel or over-bending a channel to allow the parts to springback to part print dimensions.

The introduction of AHSS creates additional challenges. First, many of the panels generate higher flow stresses, which are the combination of yield strength and work hardening during deformation. This creates higher elastic stresses in the part. Second, applying AHSS for weight reduction also requires the application of thinner sheet metal that is less capable of maintaining part shape. Third, very little or no prior experience has been generated in most companies relative to springback compensation procedures for AHSS.

Many reports state that springback problems are much greater for AHSS than for traditional HSS such as HSLA steels. However, a better description would be that the springback of AHSS is different from springback of HSLA steels. Knowledge of different mechanical properties is required. Certainly better communication between the steel supplier and the steel user is mandatory.

An example of this difference is shown in Figure 2-42. The two channels were made sequentially in a draw die with a pad on the post. The draw die was developed to attain part print dimensions with the HSLA 350/450 steel. The strain distributions between the two parts were very close with almost identical lengths of line. However, the stress distributions were very different because of the steel property differences between DP and HSLA steels (Figure 2-6).

Figure 2-42 - Two channels made sequentially in the same die.

2.C.5.a. Origins of Springback

When sheet metal is plastically deformed into a part, the shape of the part always deviates somewhat from the shape of punch and die after removal from the tooling. This dimensional deviation of the part is known as springback. Springback is caused by elastic recovery of the part, which can be illustrated simply on the stress-strain curves shown in Figure 2-43.

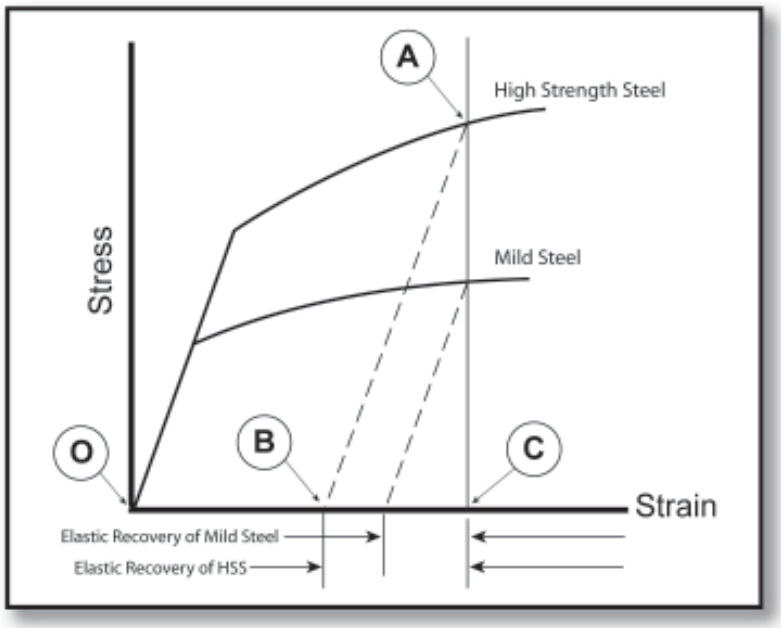


Figure 2-43 - Schematic showing amount of springback is proportional to stress.

Unloading (by removing all external forces and moments) from the plastic deformation level A would follow line AB to B, where OB is the permanent deformation (plastic) and BC is the recovered deformation (elastic). Although this elastic recovered deformation at a given location is very small, it can cause significant shape change due to its mechanical multiplying effect on other locations when bending deformation and/or curved surfaces are involved.

The magnitude of springback is governed by the tooling and component geometry. When part geometry prevents complete unloading (relaxing) of the elastic stresses, the elastic stresses remaining in the part are called residual stresses. The part then will assume whatever shape it can to minimize the total remaining residual stresses. If all elastic stresses cannot be relieved, then creating a uniformly distributed residual stress pattern across the sheet and through the thickness will help eliminate the source of mechanical multiplier effects and thus lead to reduced springback problems.

In general, springback experienced in AHSS parts is greater than that experienced in mild or HSLA steels. The expected springback is a function of the as-formed flow stress. Since AHSS have higher as-formed flow stresses for equal part-forming strains, springback generally will be higher for AHSS.

2.C.5.b. Types of Springback

Three modes of springback commonly found in channels and underbody components are angular change, sidewall curl, and twist.

Angular Change

Angular change, sometimes called springback, is the angle created when the bending edge line (the part) deviates from the line of the tool. The springback angle is measured off the punch radius (Figure 2-44). If there is no sidewall curl, the angle is constant up the wall of the channel.

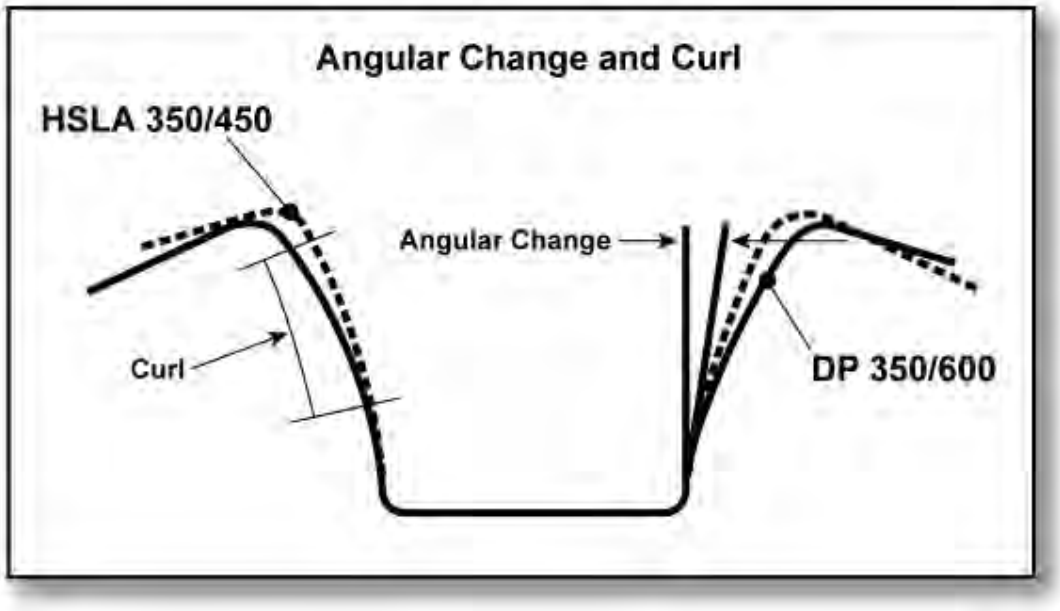


Figure 2-44 - Schematic showing difference between angular change and sidewall curl.

Angular/cross-section change is caused by stress difference in the sheet thickness direction when a sheet metal bends over a die radius. This stress difference in the sheet thickness direction creates a bending moment at the bending radius after dies are released, which results in the angular change. The key to eliminating or minimizing the angular change is to eliminate or to minimize this bending moment.

Sidewall Curl

Sidewall curl is the curvature created in the side wall of a channel (Figures 2-42 and 2-44). This curvature occurs when a sheet of metal is drawn over a die/punch radius or through a draw bead. The primary cause is uneven stress distribution or stress gradient through the thickness of the sheet metal. This stress is generated during the bending and unbending process.

During the bending and unbending sequence, the deformation histories for both sides of the sheet are unlikely to be identical. This usually manifests itself by flaring the flanges, which is an important area for joining to other parts. The resulting sidewall curl can cause assembly difficulties for rail or channel sections that require tight tolerance of mating faces during assembly. In the worst case, a gap resulting from the sidewall curl can be so large that welding is not possible.

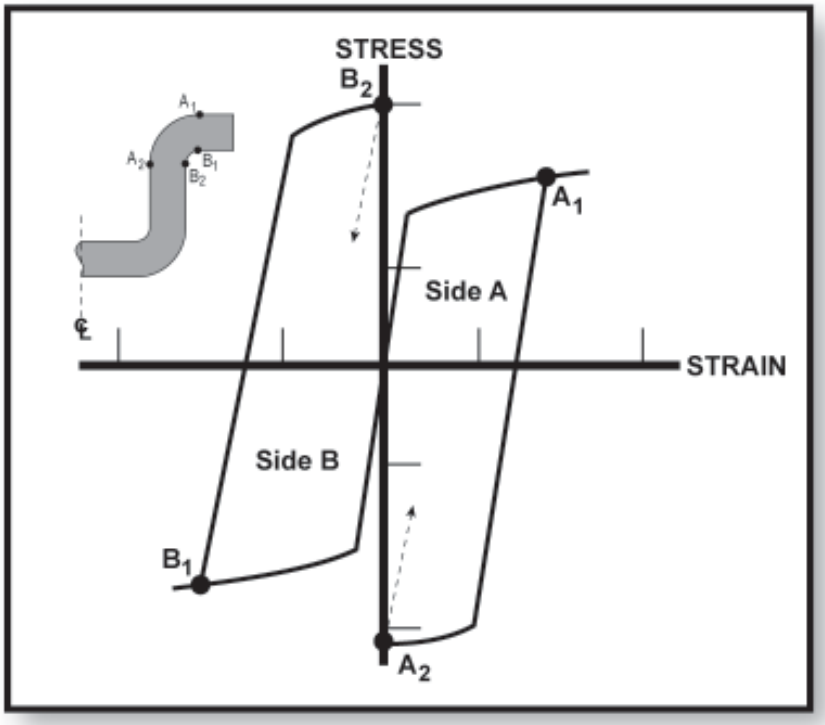


Figure 2-45 - Origin and mechanism of sidewall curl.

Figure 2-45 illustrates in detail what happens when sheet metal is drawn over the die radius (a bending and unbending process). The deformation in side A changes from tension (A_1) during bending to compression (A_2) during unbending. In contrast, the deformation in side B changes from compression (B_1) to tension (B_2) during bending and unbending. As the sheet enters the sidewall, side A is in compression and side B is in tension, although both sides may have similar amounts of strain. Once the punch is removed from the die cavity (unloading), side A tends to elongate and side B to contract due to the elastic recovery causing a curl in the sidewall.

This difference in elastic recovery in side A and side B is the main source of variation in sidewall curl along the wall. The higher the strength of the deformed metal, the greater the magnitude and difference in elastic recovery between sides A and B and the increase in sidewall curl. The strength of the deformed metal depends not only on the as-received yield strength, but also on the work hardening capacity. This is one of the key differences between conventional HSS and AHSS. Clearly, the rule for minimizing the sidewall curl is to minimize the stress gradient through the sheet thickness.

DIFFERENCE BETWEEN HSS AND AHSS **-** The difference in strain hardening between conventional HSS and AHSS explains how the relationship between angular change and sidewall curl can alter part behaviour. Figure 2-46 shows the crossover of the true stress – true strain curves when the two steels are specified by equal tensile strengths. The AHSS have lower yield strengths than traditional HSS for equal tensile strengths. At the lower strain levels usually encountered in angular change at the punch radius, AHSS have a lower level of stress and therefore less springback.

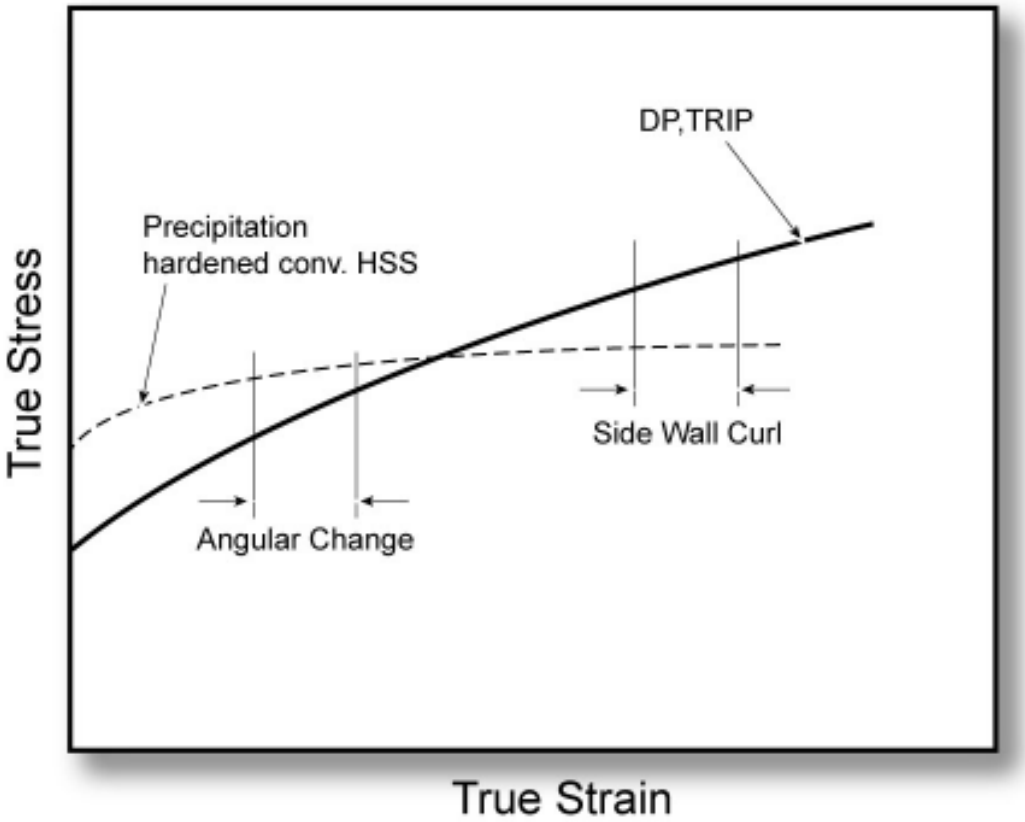


Figure 2-46 - Schematic description of the effect of hardening properties on springback.[K-4]

This difference for steels of equal tensile strength (but different yield strengths) is shown in Figure 2-47. Of course, the predominant trend is increasing angular change for increasing steel strength.

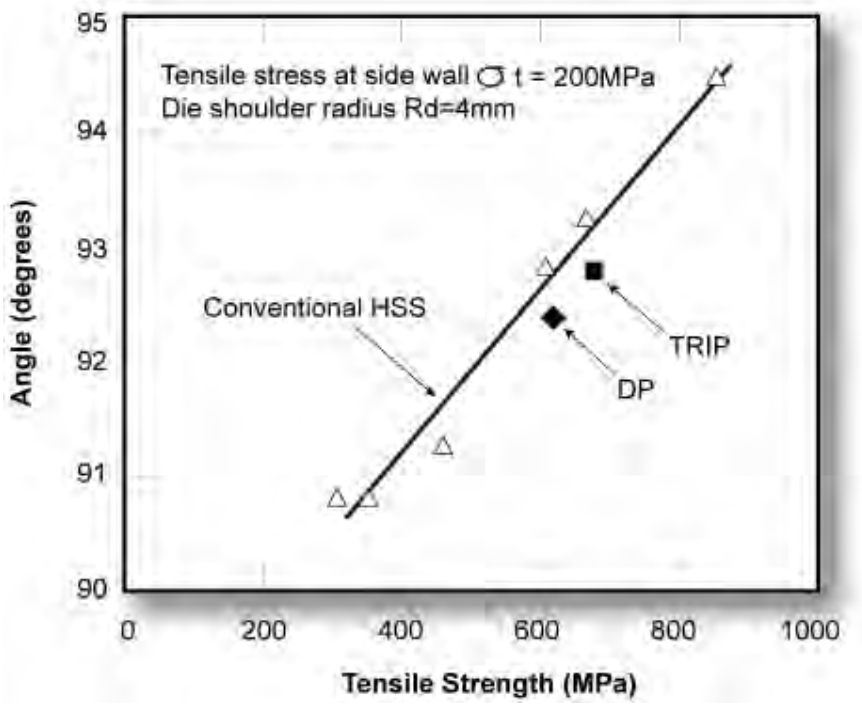


Figure 2-47 - The AHSS have less angular change at the punch radius for equal tensile strength steels.[K-4]

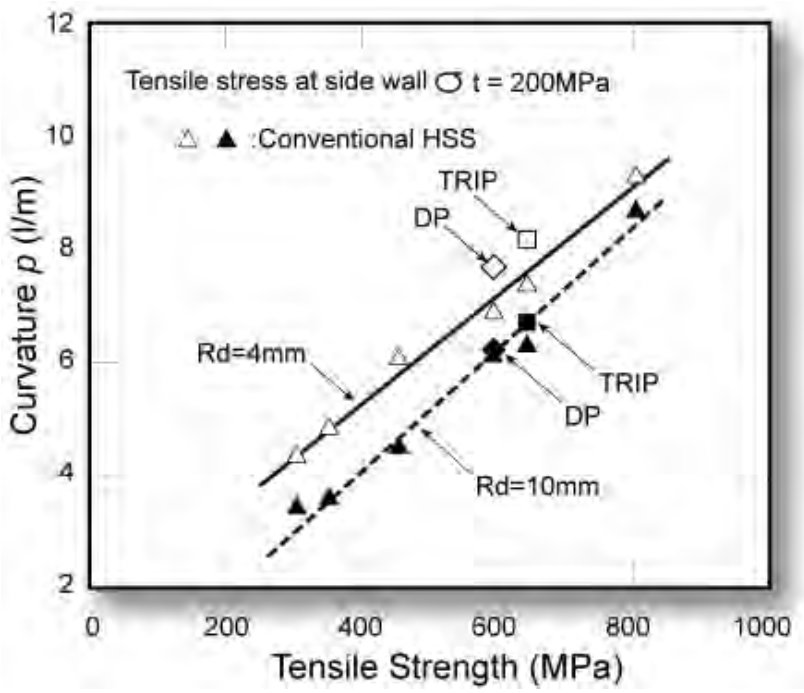


Figure 2-48 - The AHSS have greater sidewall curl for equal tensile strength steels.[N-2]

Sidewall curl is a higher strain event because of the bending and unbending of the steel going over the die radius and any draw beads. For the two stress–strain curves shown in Figure 2-46, the AHSS now are at a higher stress level with increased elastic stresses. Therefore, the sidewall curl is greater for the AHSS (Figure 2-48).

Now assume that the comparison is made between a conventional HSS and an AHSS specified with the same yield stress. Figure 2-46 would then show the stress–strain curve for the AHSS is always greater (and sometimes substantially greater) than the curve for HSS. Now the AHSS channel will have greater springback for both angular change and sidewall curl compared to the HSS channel. This result would be similar to the channels shown in Figure 2-42.

These phenomena are dependant on many factors, such as part geometry, tooling design, process parameter, and material properties, and in some cases, they may not even appear. However, the high work-hardening rate of the DP and TRIP steels causes higher increases in the strength of the deformed steel for the same amount of strain. Therefore, any differences in tool build, die and press deflection, location of pressure pins, and other inputs to the part can cause varying amounts of springback - even for completely symmetrical parts.

Twist

Twist is defined as two cross-sections rotating differently along their axis. Twist is caused by torsion moments in the cross-section of the part. The torsional displacement (twist) develops because of unbalanced springback and residual stresses acting in the part to create a force couple, which tends to rotate one end of the part relative to another. As shown in Figure 2-49 the torsional moment can come from the in-plane residual stresses in the flange, the sidewall, or both.

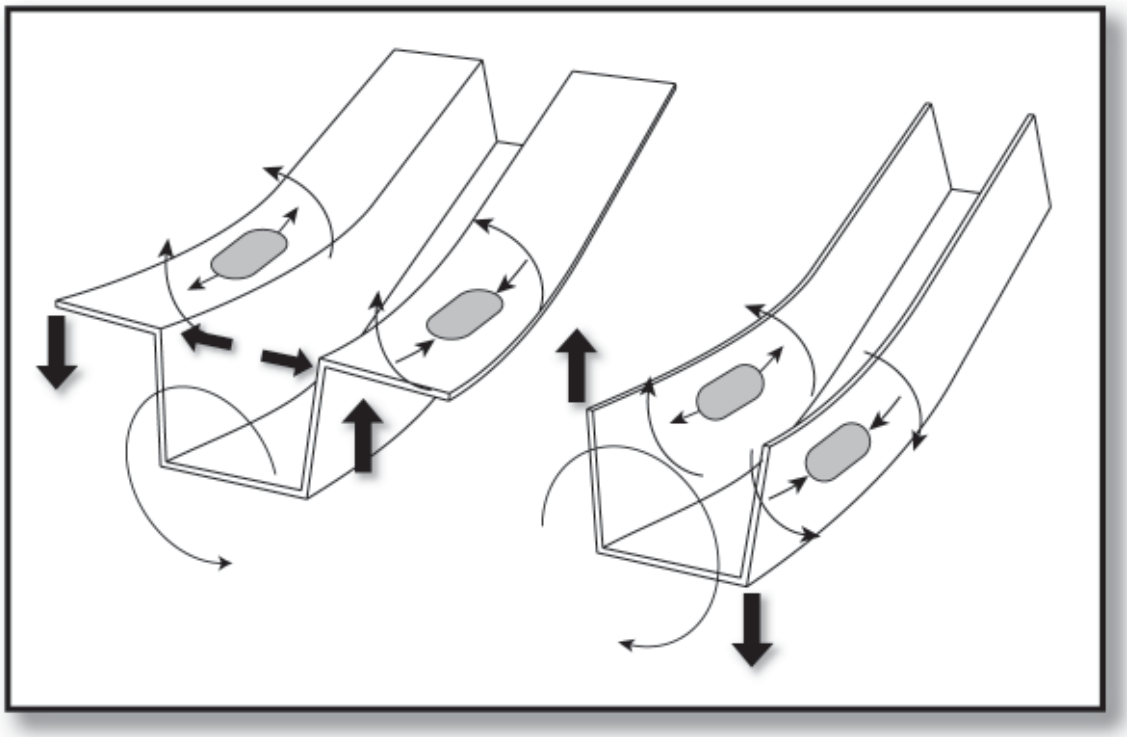


Figure 2-49 - Torsion Moment created flange or sidewall residual stresses.[Y-2]

The actual magnitude of twist in a part will be determined by the relationship between unbalanced stresses on the part and the stiffness of the part in the direction of the twist. Low torsional stiffness values in long, thin parts are the reason high aspect ratio parts have significantly higher tendencies to twist. There is also a lever effect, whereby the same amount of twist will result in a larger displacement in a long part than would be the case in a shorter part with a similar twist angle.

The tendency for parts to twist can be overcome by reducing the imbalance in the residual stresses forming the force couple that creates the torsional movement. Unbalanced forces are more likely in unsymmetrical parts, parts with wide flanges or high sidewalls, and in parts with sudden changes in cross section. Parts with unequal flange lengths or non-symmetric cutouts will be susceptible to twist due to unbalanced springback forces generated by these non-symmetrical features.

Even in geometrically symmetrical parts, unbalanced forces can be generated if the strain gradients in the parts are non-symmetrical. Some common causes of non-symmetrical strains in symmetrical parts are improper blank placement, uneven lubrication, uneven die polishing, uneven blankholder pressure, misaligned presses, or broken/worn draw beads. These problems will result in uneven material draw-in with higher strains and higher elastic recoveries on one side of the part compared to the other, thereby generating a force couple and inducing twist.

Twist can also be controlled by maximizing the torsional stiffness of the part - by adding ribs or other geometrical stiffeners or by redesigning or combining parts to avoid long, thin sections that will have limited torsional stiffness.

Global Shape Change

Global shape changes, such as reduced curvature when unloading the panel in the die, are usually corrected by springback compensation measures. The key problem is minimizing springback variation during the run of the part and during die transition. One study showed that the greatest global shape (dimensional) changes were created during die transition.[A-1]

Surface Disturbances

Surface disturbances develop from reaction to local residual stress patterns within the body of the part. Common examples are high and low spots, oil canning, and other local deformations that form to balance total residual stresses to their lowest value.

2.C.5.c. Springback Correction

Forming of a part creates elastic stresses unless the forming is performed at a higher temperature range where stress relief is accomplished before the part leaves the die. An example of the latter condition is HF steels. Therefore, some form of springback correction is required for bring the part back to part print. This springback correction can take many forms.

The first approach is to apply an additional process that changes undesirable elastic stresses to less damaging elastic stresses. One example is a post-stretch operation that reduces sidewall curl by changing the tensile-to-compressive elastic stress gradient through the thickness of the sidewall to all tensile elastic stresses though the thickness. Another example is over-forming panels and channels so that the release of elastic stresses brings the part dimensions back to part print instead of becoming undersized.

A second approach is to modify the process and/or tooling to reduce the level of elastic stresses actually imparted to the part during the forming operation. An example would be to reduce sidewall curl by replacing sheet metal flowing through draw beads and over a die radius with a simple 90 degree bending operation.

A third approach for correcting springback problems is to modify product design to resist the release of the elastic stresses. Mechanical stiffeners are added to the part design to lock in the elastic stresses to maintain desired part shape.

All three approaches are discussed in detail in this unit. While most are applicable to all higher strength steels, the very high flow stresses encountered with AHSS make springback correction high on the priority list. In addition, most of the corrective actions presented here apply to angular change and sidewall curl.

Change the Elastic Stresses

POST–STRETCH: One of the leading techniques for significant reduction of both angular change and sidewall curl is a Post-Stretch operation. An in-plane tension is applied after the bending operations in draw beads and die radii to change tensile to compressive elastic stress gradients to all tensile elastic stresses.

When the part is still in the die, the outer surface of the bend over the punch radius is in tension (Point A in Figure 2-50), while the inner surface is in compression (B). Upon release from the deforming force, the tensile elastic stresses (A) tend to shrink the outer layers and the compressive elastic forces (B) tend to elongate the inner layers. These opposite forces form a mechanical advantage to magnify the angular change. The differential stress $\Delta\sigma$ can be considered the driver for the dimensional change.

In the case of side wall curl this differential stress $\Delta\sigma$ increases as the sheet metal is work hardened going through draw beads and around the die radius into the wall of the part.

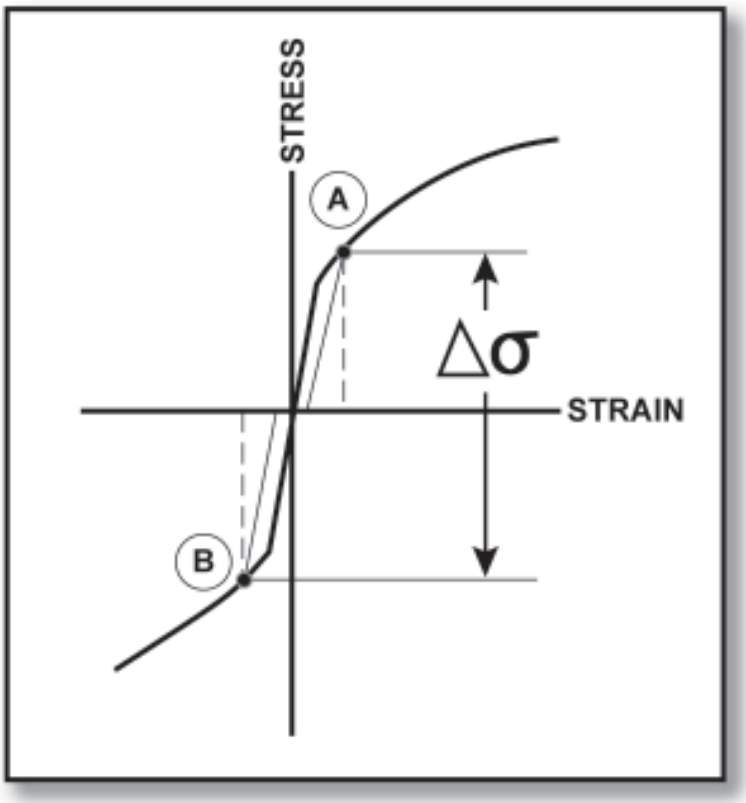


Figure 2-50 – Sheet metal bent over a punch radius has elastic stresses of the opposite sign creating a mechanical advantage to magnify angular change. Similar effects create sidewall curl for sheet metal pulled through draw beads and over die radii.

To correct this angular change and sidewall curl, a tensile stress is applied to the flange end of the wall until an approximate minimum tensile strain of 2% is generated within the sidewall of the stamping. The sequence is shown in Figure 2-51. The initial elastic states are tensile (A1) and compressive (B1). When approximately 2% tensile strain is added to A1, the strain point work hardens and moves up slightly to A2. However, when 2% tensile strain is added to B1, the compressive elastic stress state first decreases to zero, then climbs to a positive level and work hardens slightly to point B2. The neutral axis is moved out of the sheet metal. The differential stress $\Delta\sigma$ now approaches zero. Instead of bending or curving outward, the wall simply shortens by a small amount similar to releasing the load on a tensile test sample. This shortening of the wall length can be easily corrected by an increased punch stroke.

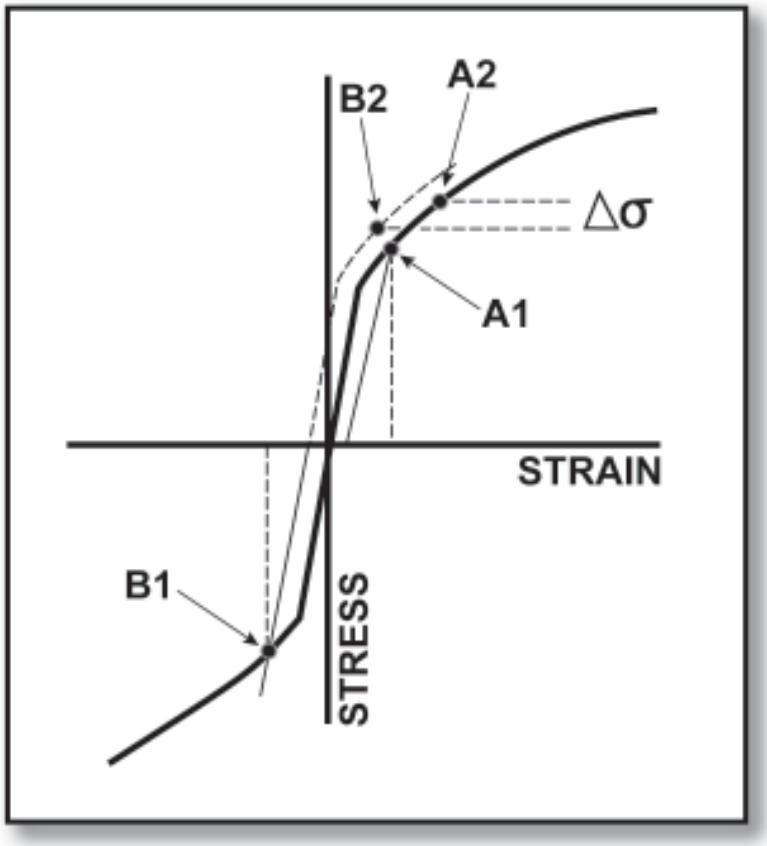


Figure 2-51 – When subjected to a 2% tensile strain, the positive to compressive stress differential shown in Figure 2-45 is now reduced to a very small amount.

The common method used to create the 2% post-stretch is form the part with a pullover plug. The bottom blank holder contains retracted movable beads and the upper blankholder contains the bead pockets. An adjustable stop block is located directly under the movable beads. At the correct amount of punch stroke, the movable beads hit the stop blocks, move up, and are forced into the sheet metal flange. This creates a blank locking action while the punch continues to deform the part. In other applications, the part is removed from the first die and inserted into a second die that locks the remaining flange. The part is then further deformed by 2%.

These post-stretch forming operations normally require significantly higher forming forces to be effective since the sidewalls have been strengthened by work hardening resulting from the forming operation. This is especially true for AHSS. Therefore, the movable draw beads may have to be replaced by movable lock beads. Even if the press is capable of generating the higher forces, caution must be taken not to neck down and tear the sheet metal bent over the punch radius.

A restrike operation may be required after trimming to ensure dimensional precision. The restrike die should sharpen the radius and provide sidewall stretch (post-stretch) of approximately 2%.

A case study on post-stretch was conducted on TRIP 450/800, DP 850/980, DP 450/750, DP 350/600, CM 490/590, and HSLA 350/450 steels using two specially designed dies[L-1]. One die had conventional metal flowing from the flange without a bead. The second die had a recessed square lock bead in the flange that created a post-stretch near the end of the stroke. As expected, the side wall curl was very small with the post-stretch die. In addition, the material tensile strength did not have much effect on the amount of springback in the post-stretch die. This translates into a more robust process.

OVER-FORMING: Many angular change problems occur when the tooling either is constructed to part print or has insufficient springback compensation. Over-forming or over-bending is required.

- Rotary bending tooling should be used where possible instead of flange wipe dies. The bending angle can be easily adjusted to correct for changes in springback due to variations in steel properties, die set, lubrication, and other process parameters. In addition, the tensile loading generated by the wiping shoe is absent.

- Multiple stage forming processes may be desirable or even required depending on the part shape. Utilize secondary operations to return a sprung shape back to part datum. Care must be taken though to ensure that any subsequent operation does not exceed the work hardening limit of the worked material. Use multi-stage computerized forming-process development to confirm strain and work hardening levels. Try to fold the sheet metal over a radius instead drawing or stretching.

- Cross-section design for longitudinal rails, pillars, and cross members can permit greater springback compensation. The rear longitudinal rail cross-section in sketch A of Figure 2-52 does not allow over-bend for springback compensation in the forming die. In addition, the forming will produce severe sidewall curl in AHSS channel-shaped cross sections. These quality issues can be minimized by designing a cross section similar to sketch B that allows for over-bend during forming. Sidewall curl is also diminished with the cross-sectional design. Typical wall opening angles should be 3-degrees for Mild steel, 6 degrees for DP 350/600 and 10 degrees for DP 850/1000 or TRIP 450/800. In addition, the cross section in sketch B will have the effect of reducing the impact shock load when the draw punch contacts the AHSS sheet. The vertical draw walls shown in sketch A require higher binder pressures and higher punch forces to maintain process control.

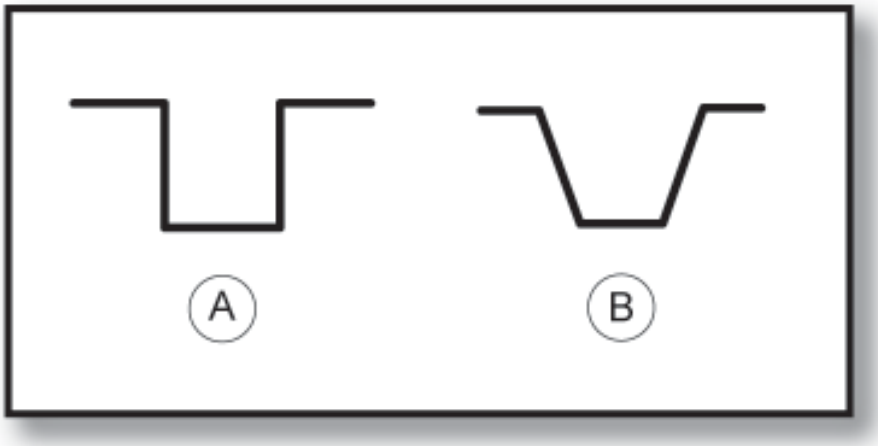


Figure 2-52 - Changing rail cross section from A to B allows easier over-bending to reduce springback problems with AHSS.[N-3]

- If over-bend must be incorporated for some parts to minimize angular change, use tool/die radii less than the part radius and use back relief for the die/punch (Figure 2-53).

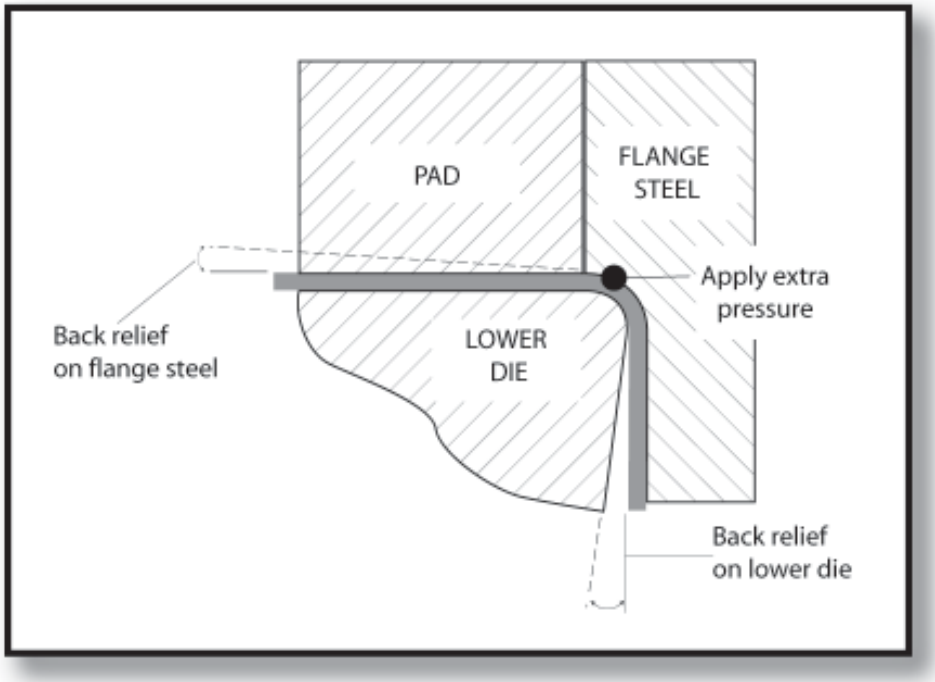


Figure 2-53 – Over-bending is assisted when back relief is provided on the flange steel and lower die.[A-2]

- If necessary, add one or two extra forming steps. For example, use pre-crown in the bottom of channel-type parts in the first step and flatten the crown in the second step to eliminate the springback at sidewall (Figure 2-54).

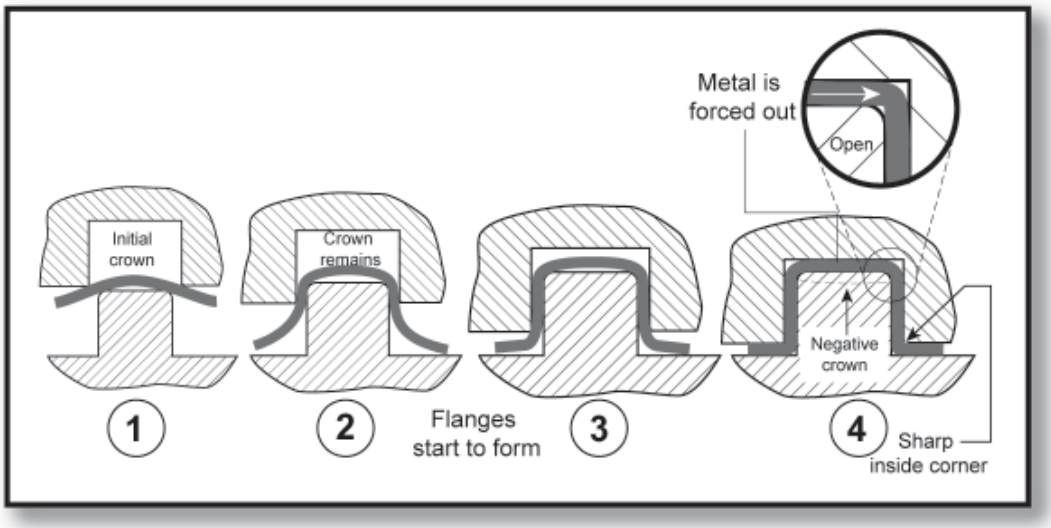


Figure 2-54 - Schematic showing how bottom pre-crown can be flattened to correct for angular springback.[A-3]

Reduce or Minimize the Elastic Stresses

Many times the design of the process, and therefore the tooling design, can drastically affect the level of the elastic stresses in the part.

FORMING THE CHANNEL WALL: Figure 2-55 shows four possible forming processes to create a hat-profile channel with different blankholder actions.

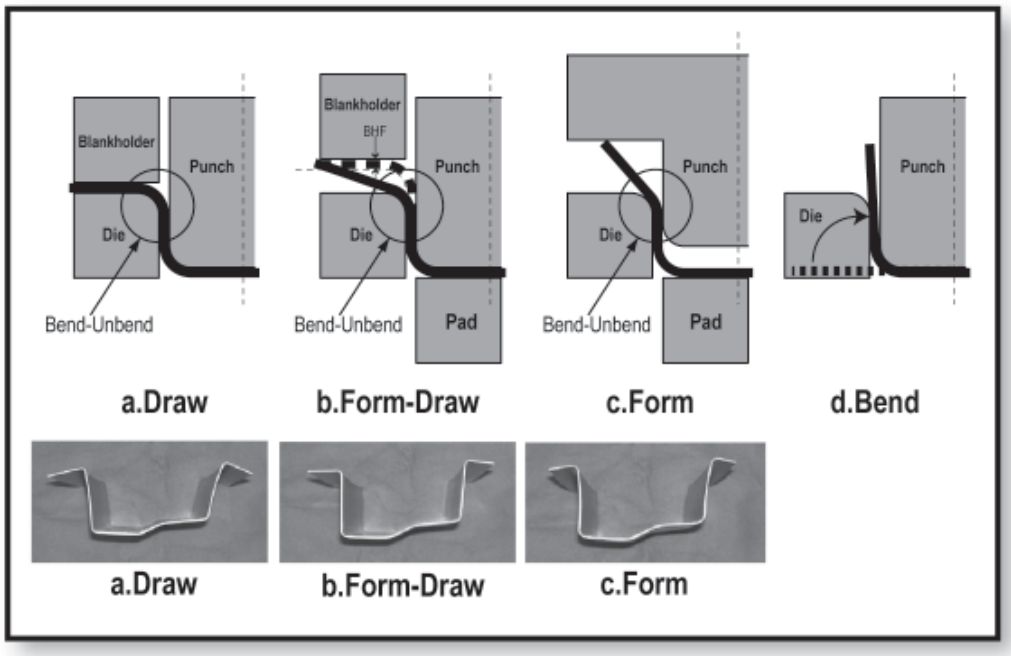


Figure 2-55 – Four processes for generating a channel for bumper reinforcement create different levels of elastic stress and springback.[K-5]

Descriptions of the four processes above:

- Draw is the conventional forming type with continuous blankholder force and all blank material undergoing maximum bending and unbending over the die radius. This forming mode creates maximum sidewall curl.
- Form-draw is a forming process in which the blank holder force is applied between the middle and last stage of forming. It is most effective to reduce the sidewall curl because bend-unbend deformation is minimized and during the last stage of forming a large tensile stress (post-stretch) can be created.
- Form process allows the flange to be formed in the last stage of forming and the material undergoes only a slight amount of bend-unbend deformation.
- Bend is a simple bending process to reduce the sidewall curl because the sidewall does not undergo one or more sequences of bend and unbend. However, an angular change must be expected.

GUIDELINES FOR DRAW AND STRETCH FORM DIES

- Equalize depth of draw as much as possible.
- Binder pressure must be increased for AHSS. For example, DP 350/600 requires a tonnage factor 2.5 times greater than that required for AKDQ of comparable thickness. Higher binder pressure will reduce panel springback.
- Maintain a 1.1t maximum metal clearance in the draw dies.
- Lubrication, upgraded die materials, and stamping process modification must be considered when drawing AHSS.
- Maintain die clearance as tight as allowed by formability and press capability to reduce unwanted bending and unbending (Figure 2-56).

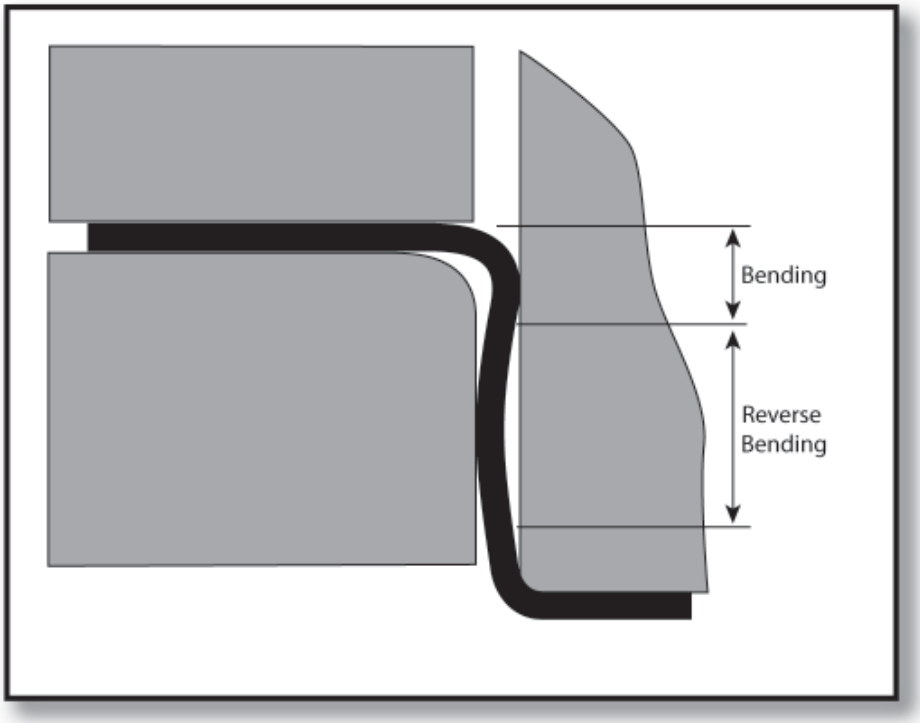


Figure 2-56 - Reducing die clearance restricts additional bending and unbending as the sheet metal comes off the die radius to minimize angular change.[Y-2]

- Stretch-forming produces a stiffer panel with less springback than drawing. Potential depth of the panel is diminished for both processes as the strength of the material increases. Deeper AHSS stampings will require the draw process.

An extensive American Iron and Steel Institute study[S-3] defined a number of tool parameters that reduced angular change (Figure 2-57A) and side wall curl (Figure 2-57B).

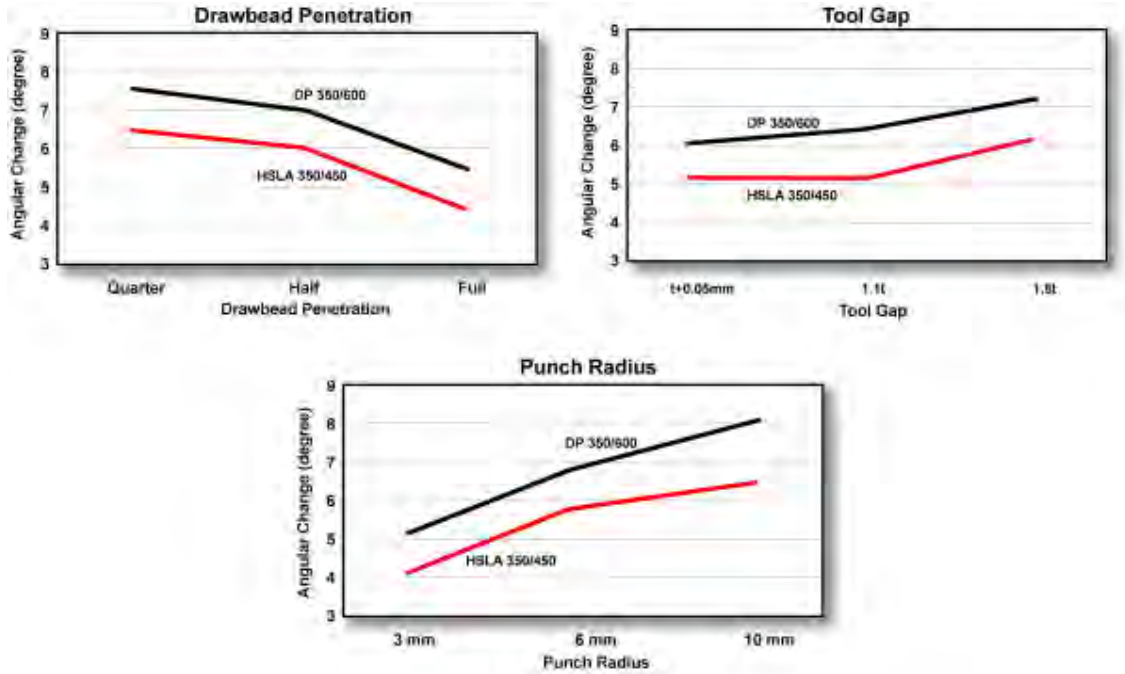


Figure 2-57A – The effect of tool parameters in angular change. The lower values are better.[S-3]

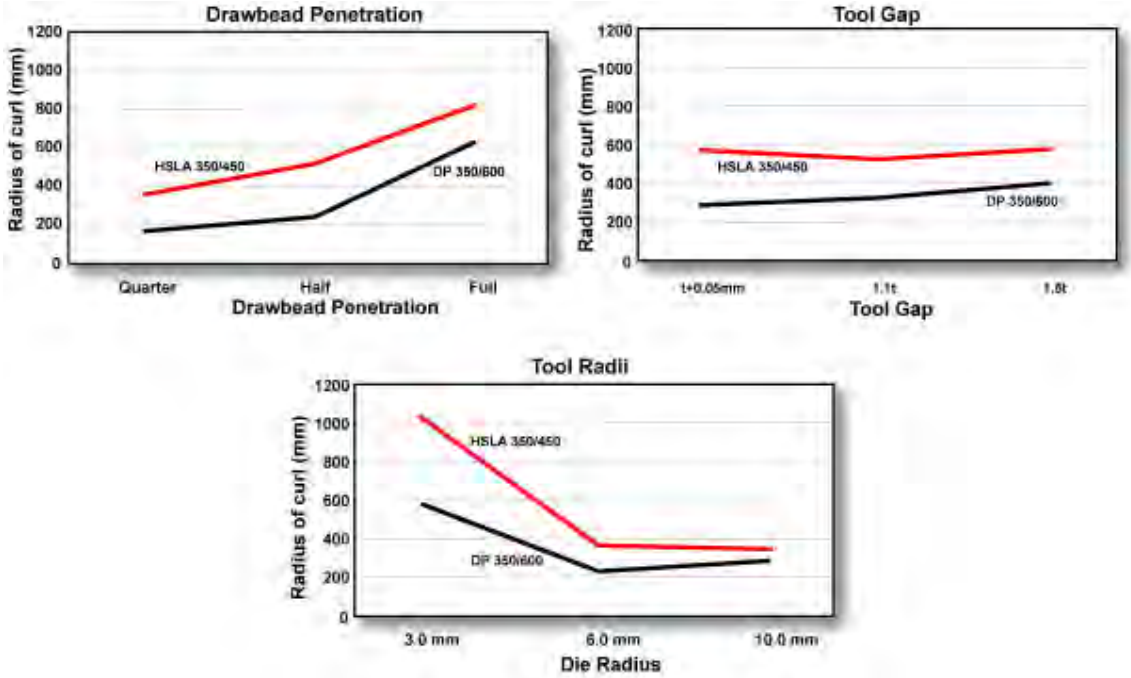


Figure 2-57B - The effect of tool parameters in sidewall curl. Higher values of radius of curl are better.[S-3]

GUIDELINES FOR FORM DIE:

- Set-up the die to allow for appropriate over-bend on sidewalls.
- Equalize the depth of forming as much as possible.
- Use a post-stretch for channel-shaped stampings. For less complex parts, one form die should be sufficient. For more geometrically complex parts, the first die will form the part with open sidewalls. The second die will finish the form in a restrike die with post-stretch of the sidewalls. Part geometry will determine the required forming process.
- Some complex parts will require a form die with upper and lower pressure pads. To avoid upstroke deformation of the part, a delayed return pressure system must be provided for the lower pad. When a forming die with upper pad is used, sidewall curl is more severe in the vertical flange than in the angular flange.
- Provide higher holding pressure. DP 350/600 requires a force double that needed for Mild steel.
- When using form dies, keep a die clearance at approximately 1.3t to minimize sidewall curl. Die clearance at 1t is not desirable since the sidewall curl reaches the maximum at this clearance.
- Do not leave open spaces in the die flange steels at the corners of the flanges. Fit the radius on both sides of metal at the flange break. Spank the flange radius at the bottom of the press stroke.
- Bottom the pad and all forming steels at the bottom of the press stroke.

PART DESIGN: Part design features should be considered as early as possible in the concept stage to allow for proper process and tooling design decisions to be made.

- Successful application of any material requires close coordination of part design and the manufacturing process. Consult manufacturing process engineers when designing AHSS parts to understand the limitations/advantages of the material and the proper forming process to be employed.
- Design structural frames (such as rails and crossbars) as open-end channels to permit forming operations rather than draw die processes. AHSS stampings requiring draw operations (closed ends) are limited to a reduced depth of draw. Half the draw depth permitted for AKDQ is the rule of thumb for AHSS such as DP 350/600. Less complex, open-ended stamped channels are less limited in depth.
- Design AHSS channel shaped part depth as consistent as possible to avoid forming distortions. All shape transitions should be gradual to avoid distortions, especially in areas of metal compression. Minimize stretch/compression flanges whenever possible.
- Design the punch radius as sharp as formability and product/style allow. Small bend radii (<2t) will decrease the springback angle and variation (Figure 2-58). However, stretch bending will be more difficult as yield strength increases. In addition, sharp radii contribute to excessive thinning.

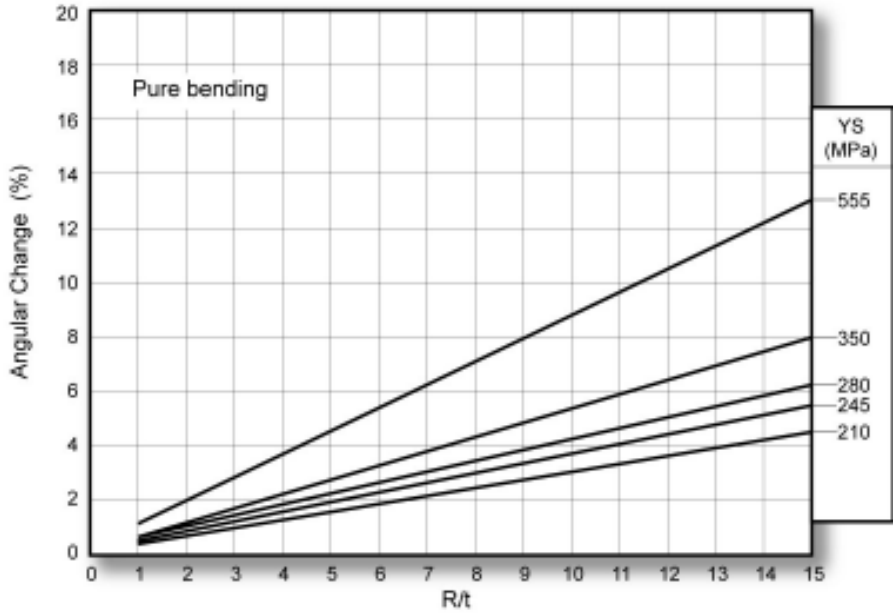


Figure 2-58- Angular changes are increased by YS and bend radius to sheet thickness ratio.[S-2]

- Curved parts with unequal length sidewalls in the fore-aft direction will develop torsional twist after forming. The shorter length wall can be under tension from residual forming stresses. Torsional twist is more pronounced with the higher strength steels. Conventional guidelines for normal steels can also be applied to AHSS to avoid asymmetry that accentuates the possibility for part twist. However, the greater springback exhibited by AHSS means extra caution should taken to ensure symmetry is maintained as much as possible.

- Inner and outer motor-compartment rails also require an optimized cross-section design for AHSS applications. Sketch A in Figure 2-59 shows a typical rectangular box section through the inner and outer rails. This design will cause many problems for production due to sidewall curl and angular change. The hexagonal section in sketch B will reduce sidewall curl and twist problems, while permitting over-bend for springback compensation in the stamping dies.

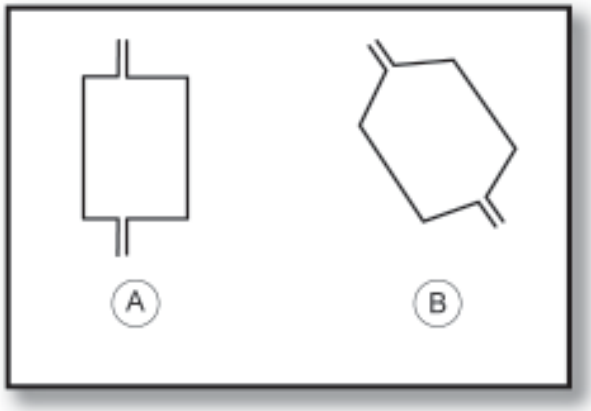


Figure 2-59 - Changing rail cross section from A to B reduces springback problems with AHSS.[N-3]

- Springback computer simulations should be used whenever possible to predict the trend of springback and to test the effectiveness of solutions.

- Design the part and tool in such a way that springback is desensitized to variations in material, gauge, tools and forming processes (a robust system and process) and that the effects of springback are minimized rather than attempt to compensate for it.

Lock In the Elastic Stresses

- Where part design allows, mechanical stiffeners can be inserted to prevent the release of the elastic stresses and reduce various forms of springback (Figure 2-60). However, all elastic stresses not released remain in the part as residual or trapped stresses. Subsequent forming, trimming, punching, heating, or other processes may unbalance the residual stress and change the part shape. Twist also can be relieved by adding strategically placed beads, darts, or other geometric stiffeners in the shorter length wall to equalize the length of line.

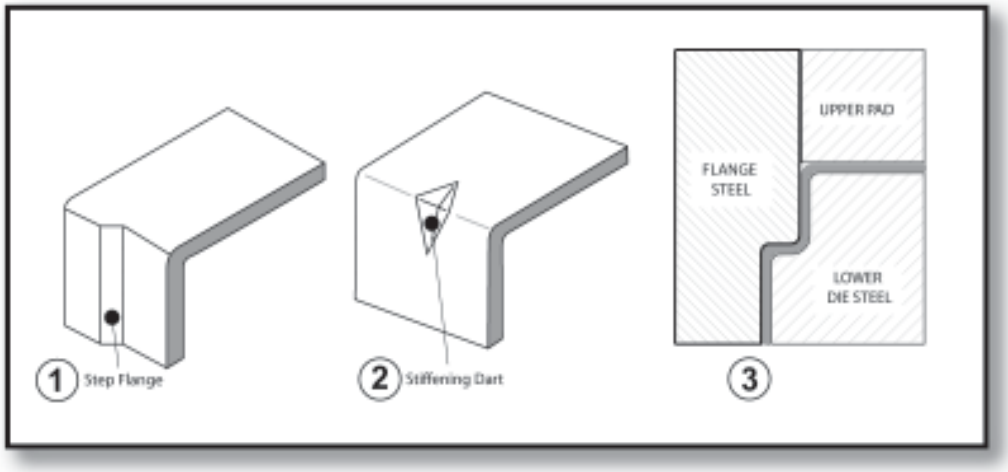


Figure 2-60 – Mechanical stiffeners can be used to lock in the elastic stresses and the part shape.[A-2]

2.C.5.d. Key Points

- Angular change and sidewall curl escalate with increasing as-formed yield strength and decrease with increasing material thickness.
- For equal yield strengths, DP steels exhibit more angular change and sidewall curl than conventional HSLA steels. The springback behaviours of TRIP steels are between DP and HSLA steels.
- The sidewall curl appears to be more sensitive to the material and set-up in a channel draw test.
- The angular change decreased with smaller tooling radii and tool gap, but sidewall curl showed mixed results for smaller tooling radii and tool gap. Both angular change and sidewall curl were reduced with a larger drawbead restraining force.
- Numerous process modifications are available to remove (or at least minimize and stabilize) the different modes of springback found in channels and similar configurations.

2.C.6. Blanking, Shearing, and Trim Operations

2.C.6.a. General Comments

AHSS exhibit high work hardening rates, resulting in improved forming capabilities compared to conventional HSS. However, the same high work hardening creates higher strength and hardness in sheared or punched edges. In addition, laser cutting samples will also lead to highly localized strength and hardness increases in the cut edge. In general, AHSS can be more sensitive to edge condition because of this higher strength. Therefore, it is important to obtain a good quality edge during the cutting operation. With a good edge, both sheared and laser cut processes can be used to provide adequate formability.

To avoid unexpected problems during a program launch, production intent tooling should be used as early in the development as possible. For example, switching to a sheared edge from a laser-cut edge may lead to problems if the lower ductility, usually associated with a sheared edge, is not accounted for during development.

2.C.6.b. Tool Wear, Clearances, and Burr Height

Cutting and punching clearances should be increased with increasing sheet material strength. The clearance range from about 6% of the sheet material thickness for Mild steel up to about 10 or 14% for the highest grade with a tensile strength of about 1400 MPa.

Two hole punching studies.[C-2] were conducted with Mild steel and AHSS. The first measured tool wear, while the second studied burr height formation. The studies showed that wear when punching AHSS with surface treated high quality (PM) tool steels is comparable with punching Mild steel with conventional tools. If burr height is the criterion, high quality tool steels may be used with longer intervals between resharpening when punching AHSS, since the burr height does not increase as quickly with tool wear as when punching Mild steel with conventional tool steels.

Tested were 1.0 mm sheet metals: Mild 140/270, A80 = 38%, DP 350/600, A80 = 20%, DP 500/800, A80=8%, and MS1150/1400, A80 = 3%. Tool steels were W.Nr. 1.2363 / AISI A2 with a hardness of 61 HRC and a 6% clearance for Mild steel tests. PM tools with a hardness range of 60-62 HRC were used for the AHSS tests. For the DP 350/600, the punch was coated with CVD (TiC) and the clearance was 6%. Tool clearances were 10 % for the MS 1150/1400 and 14 % for DP 500/800.

Punching test results: The worn cross-section of the punch was measured after 200,000 punchings. For comparison, relative tool wear with AHSS was compared to Mild steel with A2 tooling, which was about 2000 ìm² for the 200,000 punchings. Test results are shown in Figure 2-61.

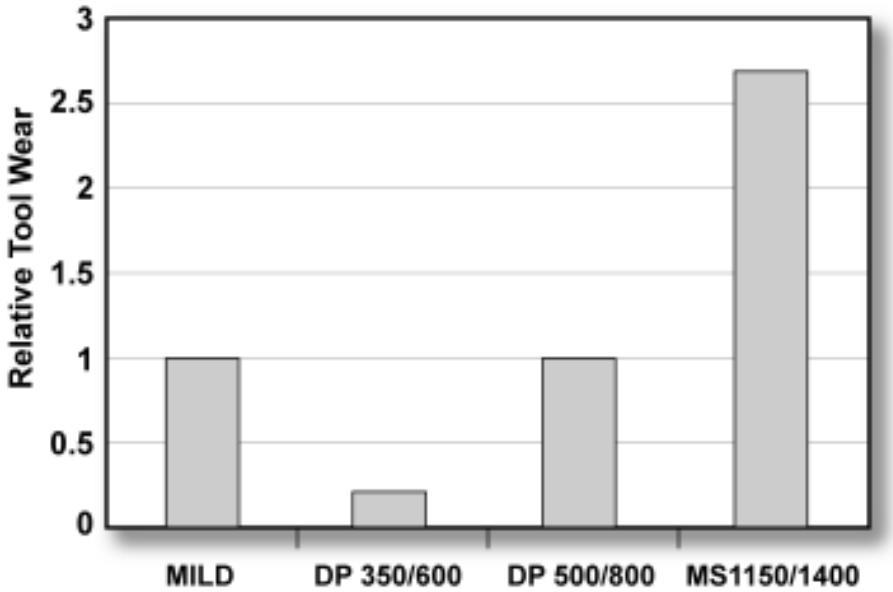


Figure 2-61 – Punching up to DP 500/800 with surface treated high quality tool steels can be comparable to Mild steel with conventional tools.[C-2]

Burr height tests: The increasing burr height is often the reason for resharpening punching tools. For Mild steels the burr height increases continuously with tool wear. This was found not to be the case for the AHSS in Figure 2-62. Two AHSS tested were DP 500/800 and MS 1150/1400. The burr heights were measured in four locations and averaged. The averages for the two AHSS were so close that they are plotted as a single line.

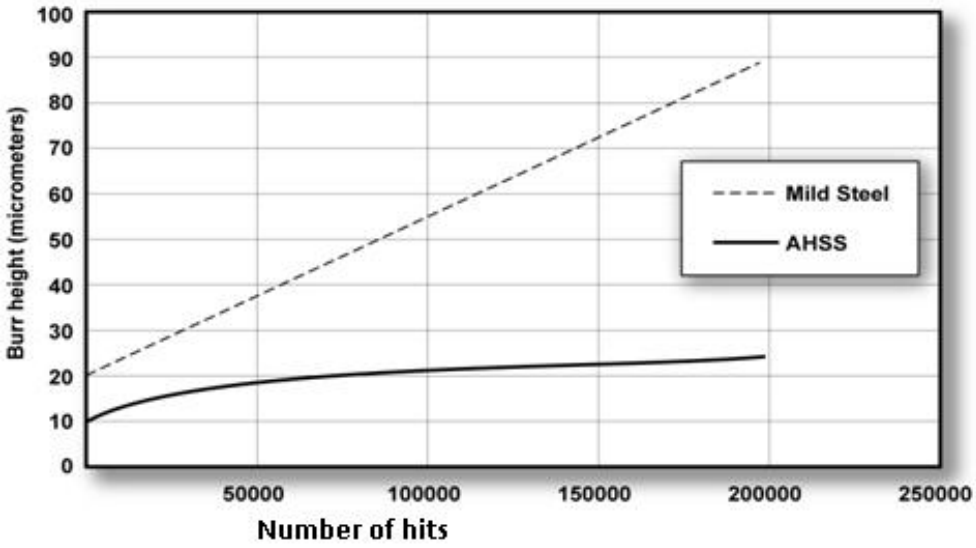


Figure 2-62 - Burr height comparison for Mild steel and AHSS as a function of the number of hits. Results for DP 500/800 and MS 1150/1400 are identical and shown as the AHSS curve.[C-2]

The plausible explanation for Figure 2-62 is that both materials initially have a burr height related to the material strength and the sharpness of the tools. AHSS has a more brittle fracture and therefore the burr height has a maximum possible height. This height is reached when the maximum local elongation is obtained during the punching, after which the burr height does not increase. The Mild steel, which is more formable, will continue to generate higher burr height with increased tool wear.

The burr height increased with tool wear and increasing die clearance when punching Mild steel. AHSS may require a higher grade tool steel or surface treatment to avoid tool wear, but tool regrinding because of burrs should be less of a problem.

Additional information on tool wear is contained in Section 2.C.4.a. Tool Materials.

2.C.6.c. Key Points

- Clearances for blanking and shearing should increase as the strength of the material increases.
- Burr height increases with tool wear and increasing die clearances for shearing Mild steel, but AHSS tends to maintain a constant burr height. This means extended intervals between tool sharpening may be applicable to AHSS parts.
- Laser cut blanks used during early tool tryout may not represent normal blanking, shearing, and punching quality. Production intent tooling should be used as early as possible in the development stage.

2.C.7. Press Requirements

2.C.7.a. Force versus Energy

Both mechanical and hydraulic presses require three different capacities or ratings – maximum force, energy, and power.

The most common press concern when forming higher strength steels is whether the press is designed to withstand the maximum force required to form the stamping. Therefore, press capacity (for example, 1000 kN) is a suitable number for the mechanical characteristics of a stamping press. Capacity, or tonnage rating, indicates the maximum force that the press can apply. However, the amount of force available depends on whether the press is hydraulic or mechanically driven. Hydraulic presses can exert maximum force during the entire stroke, whereas mechanical presses exert their maximum force at a specific displacement just prior to bottom dead center. At increased distances above bottom dead center, the press capacity is reduced.

Energy consumption inherent in sheet metal forming processes is related to the true stress-true strain curve and it depends on the yield strength and the work hardening behaviour characterized by the n-value. The energy required for plastically deforming a material (force times distance) corresponds to the area under the true stress-true strain curve. Figure 2-63 shows the true stress-strain curves for two materials with equal yield strength - HSLA 350/450 and DP 350/600. Many other true stress-true strain curves can be found in Figure 2-9.

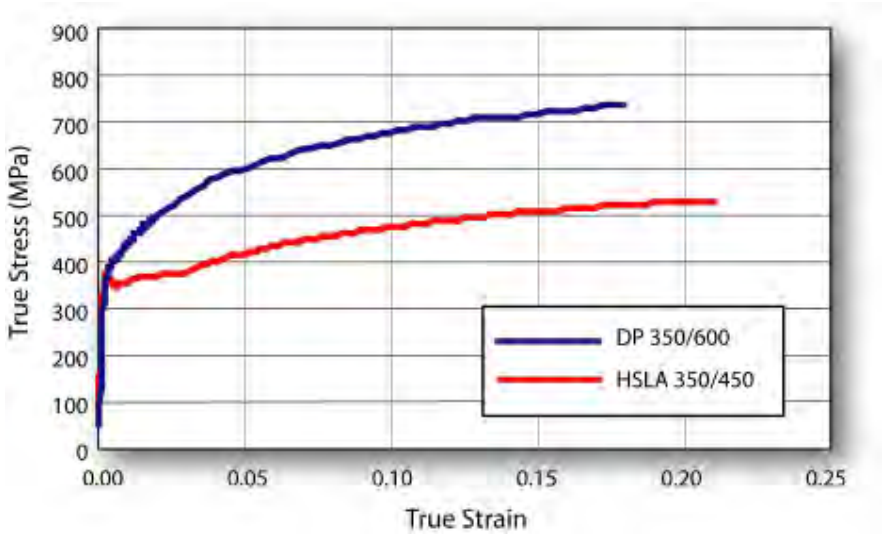


Figure 2-63 - True stress-strain curves for two materials with equal yield strength.[T-3]

The higher work hardening of the DP grade requires higher press loads when compared to the HSLA at the same sheet thickness. However, the use of AHSS is normally coupled with a reduced thickness for the stamping and the required press load would be decreased or compensated. The higher n values also tend to flatten strain gradients and further reduce the peak strains.

The required power is a function of applied forces, the displacement of the moving parts, and the speed.

Predicting the press forces needed initially to form a part is known from a basic understanding of sheet metal forming. Different methods can be chosen to calculate drawing force, ram force, slide force, or blankholder force. The press load signature is an output from most computerized forming-process development programs, as well as special press load monitors.

Example: Press Force Comparisons

The computerized forming process-development output (Figure 2-64) shows the press forces involved for drawing and embossing Mild steel approximately 1.5 mm thick, conventional HSS, and DP 350/600. It clearly shows that the forces required are dominated by the embossing phase rather than by the drawing phase.

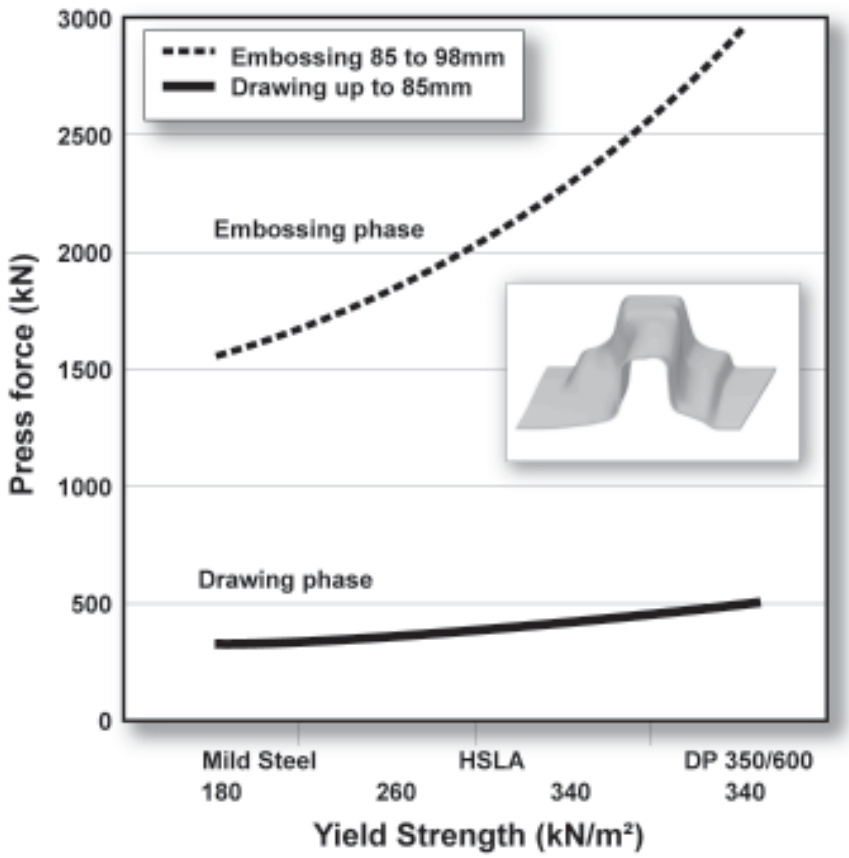


Figure 2-64 - Data demonstrates that embossing dominates the required press force rather than the drawing force.[H-3]

Sometimes the die closing force is an issue because of the variety of draw-bead geometries that demand different closing conditions around the periphery of the stamping.

Example: Press Energy Comparisons

A similar analysis (Figure 2-65) shows the press energy required to draw and emboss the same steels shown in Figure 2-64. The energy required is also dominated by the embossing phase rather than by the drawing phase, although the punch travel for embossing is only a fraction of the drawing depth.

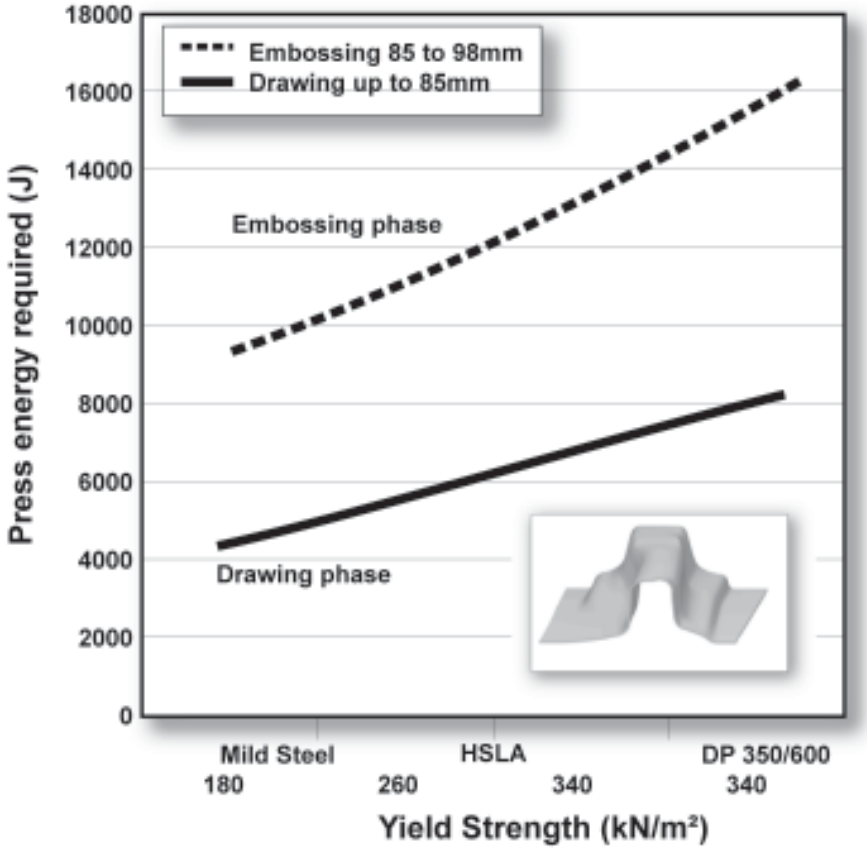


Figure 2-65 - Data showing the energy required to emboss a component is greater than for the drawing component.[H-3]

2.C.7.b. Prediction of Press Forces Using Simulative Tests

Relative press forces from Marciniak stretching tests showed AHSS grades require higher punch forces in stretch forming operations (Figure 2-66). However, applying the stretch forming mode for CP grades is not common due to the lower stretchability of CP grades.

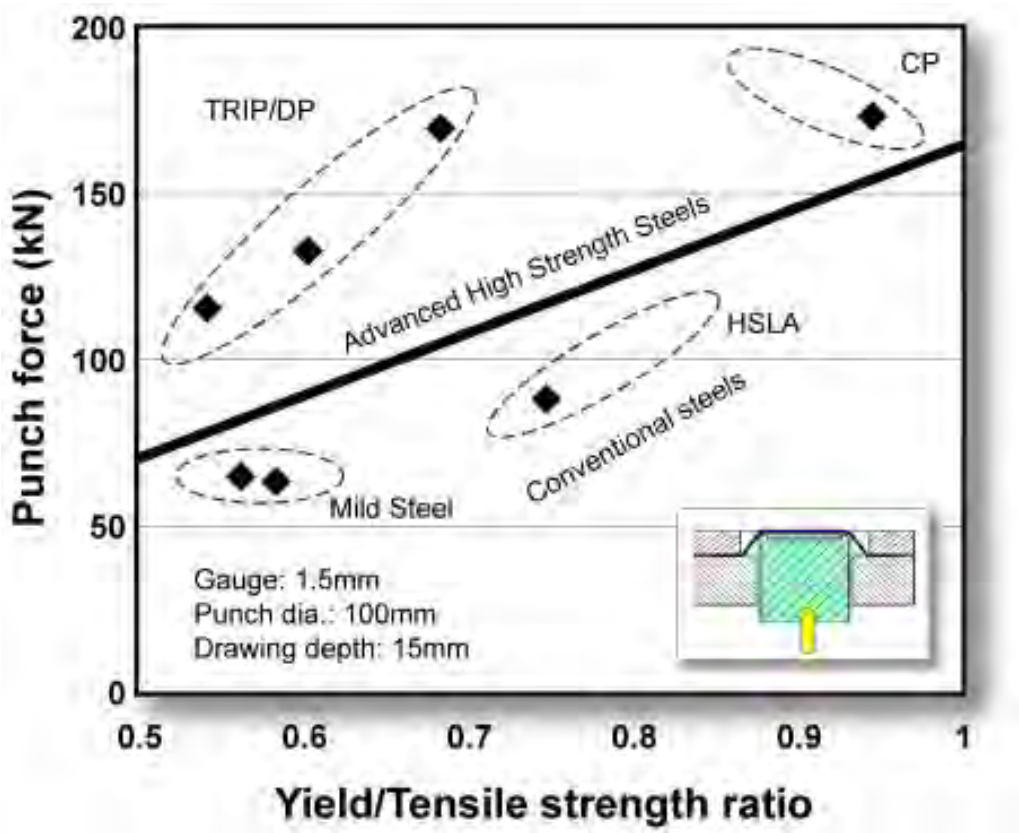


Figure 2-66 - Punch forces from Marciniak cup-stretch forming tests for AHSS and conventional steel types.[H-3]

2.C.7.c. Extrapolation From Existing Production Data

Relationships between thickness and UTS can be used as a quick extrapolation calculation of press loads for simple geometries. Figure 2-67 shows the measured press loads for the production of a cross member with a simple hat-profile made of HSLA 350/450 and DP 300/500 steels of the same thickness.

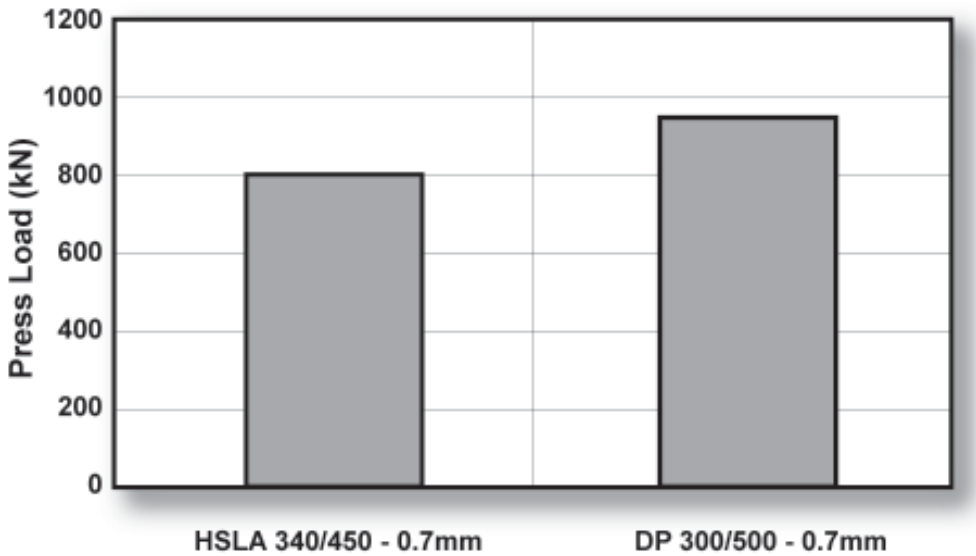


Figure 2-67 - Measured press load for a Hat-Profile Cross Member.[T-3]

Using the following equation, the press load F2 for DP 300/500 was estimated from the known press load F1 from HSLA 350/450.[T-3]

F2 is proportional to (F1) x (t_2/t_1) x (R_{m2}/R_{m1})

Where:
- F1 Old Measured Drawing Force
- F2 New Estimated Drawing Force
- t_1 Old Material Thickness
- t_2 New Material Thickness
- R_{m1} Old Tensile Strength
- R_{m2} New Tensile Strength

Steel Type	Thickness (mm) t	Measured Drawing Force [kN] F	UTS (approx.) (MPa) R_m	Estimated Drawing Force [kN]
1 = HSLA	0.7	F1 = 791	433	
2 = DP	0.7	934	522	F2 = 953

The data above compares the measured drawing force and the estimated drawing force for the DP 300/500 using the formula. A good correlation between measured and predicted drawing force was obtained. While good force estimations are possible using this extrapolation technique, the accuracy is rather limited and often overstates the load. Therefore, the calculation should be viewed as an upper boundary.

2.C.7.d. Computerized Forming-Process Development

Rules of thumb are useful to estimate press loads. A better evaluation of press loads, such as draw force, embossment force, and blank holding force, can be obtained from computerized tools. Many of the programs enable the user to specify all of the system inputs. This is especially important when forming AHSS because the high rate of work hardening has a major effect on the press loads. In addition, instead of using a simple restraining force on blank movement, analyses of the physical draw beads must be calculated.

Another important input to any calculation is the assumption that the tools are rigid during forming, when in reality the tools deform elastically in operation. This discrepancy leads to a significant increase in the determined press loads, especially when the punch is at home position. Hence, for a given part, the draw depth used for the determination of the calculated press load is an important parameter. For example, if the nominal draw depth is applied, press loads may be overestimated. The deflection (sometimes called breathing) of the dies is accentuated by the higher work hardening of the AHSS.

Similarly, the structure, platens, bolsters, and other components of the press are assumed to be completely rigid. This is not true and causes variation in press loads, especially when physical tooling is moved from one press to another.

If no proven procedure for computerized prediction is available, validation of the empirical calculations is recommended. Practical pressing tests should be used to determine the optimum parameter settings for the simulation. Under special situations, such as restrike operation, it is possible that computerized analyses may not give a good estimation of the press loads. In these cases, computerized tools can suggest forming trends for a given part and assist in developing a more favourable forming-process design.

Most structural components include design features to improve local stiffness. Features requiring embossing processes are mostly formed near the end of the ram cycle. Predicting forces needed for such a process is usually based on press shop experiences applicable to conventional steel grades. To generate comparable numbers for AHSS grades, computerized forming process-development is recommended.

2.C.7.e. Case Study for Press Energy

The following study is a computerized analysis of the energy required to form a cross member with a hat-profile and a bottom embossment at the end of the stroke (Figure 2-68).

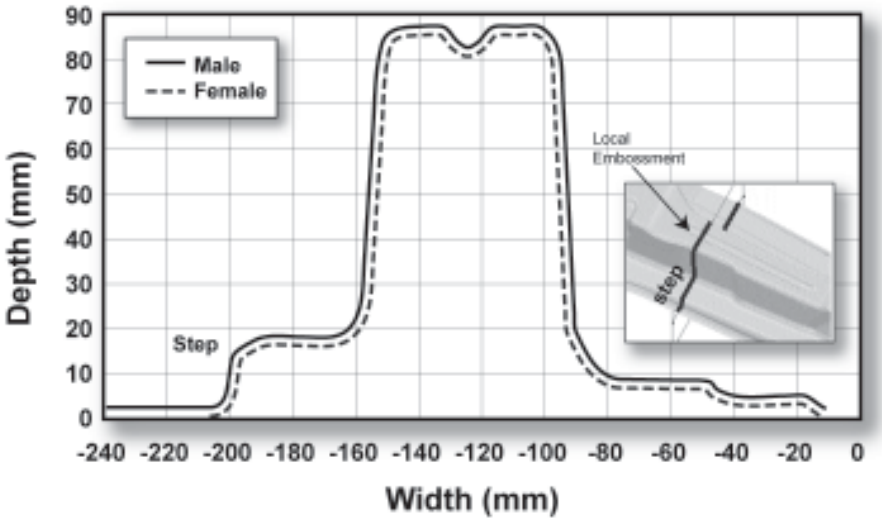


Figure 2-68 - Cross-section of a component having a longitudinal embossment to improve stiffness locally.[H-3]

Increasing energy is needed to continue punch travel. The complete required energy curves are shown in Figure 2-69 for Mild, HSLA 250/350, and DP 350/600 steels. The three dots indicate the start of the embossment formation at a punch movement of 85 mm.

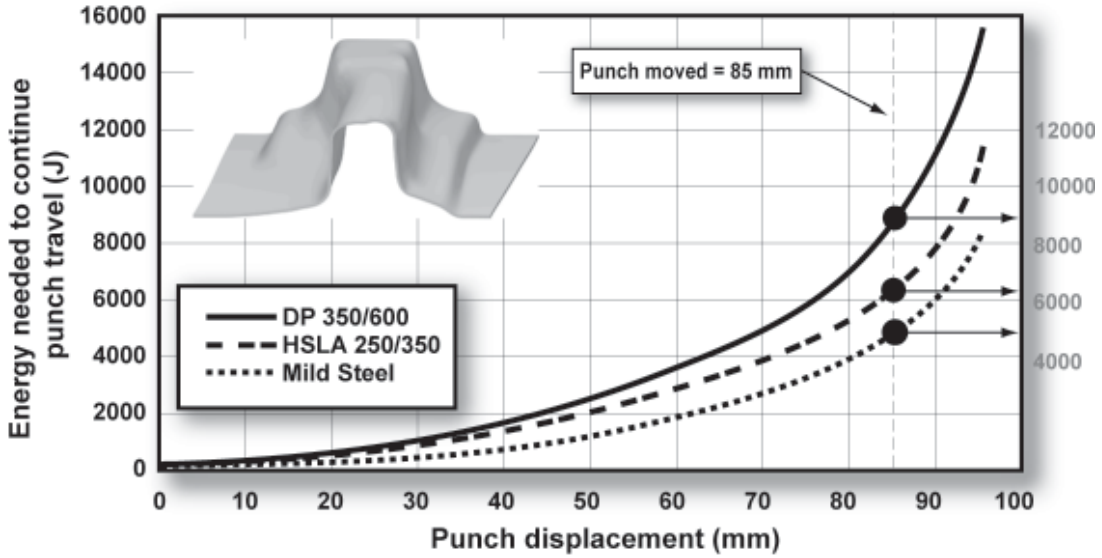


Figure 2-69 - Computerized analysis showing the increase in energy needed to form the component with different steel grades. Forming the embossment begins at 85 mm of punch travel.[H-3]

The last increment of punch travel to 98 mm requires significantly higher energy, as shown in Figure 2-70. Throughout the punch travel however, the two higher strength steels appear to maintain a constant proportional increase over the Mild steel.

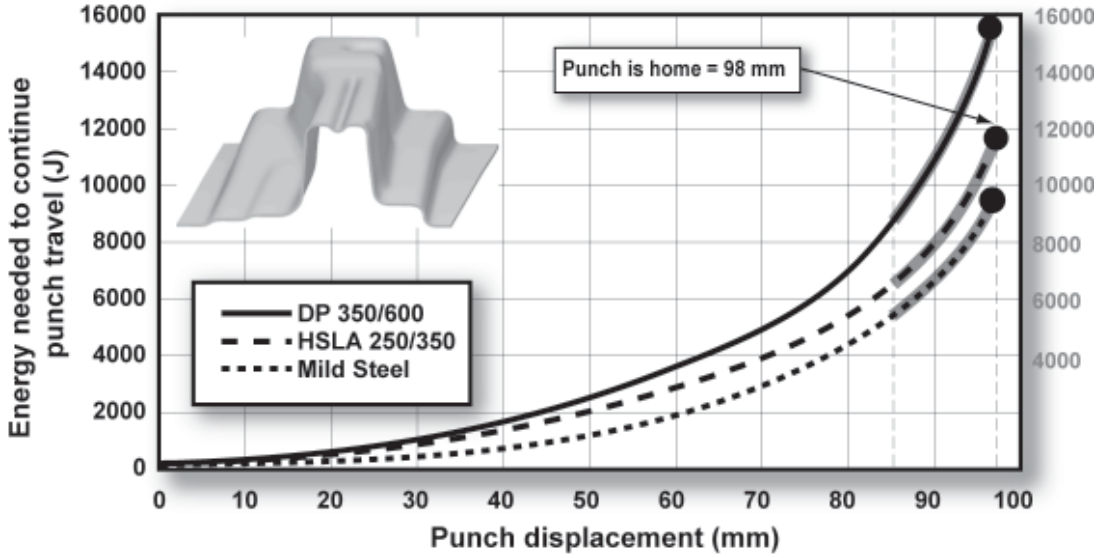


Figure 2-70 - A further increase in energy is required to finish embossing.[H-3]

2.C.7.f. Setting Draw Beads

A considerable force is required from a nitrogen-die cushion in a single-acting press to set draw beads in AHSS before drawing begins. The nitrogen-die cushion may be inadequate for optimum pressure and process control. In some cases, binder separation may occur because of insufficient cushion tonnage, resulting in a loss of control for the stamping process.

The high impact load on the cushion may occur several inches up from the bottom of the press stroke. Since the impact point in the stroke is both a higher velocity point and a derated press tonnage, mechanical presses are very susceptible to damage due to these shock loads. Additional flywheel energy is dissipated by the high shock loads well above bottom dead center of the stroke.

A double-action press will set the draw beads when the outer slide approaches bottom dead center where the full tonnage rating is available and the slide velocity is substantially lower. This minimizes any shock loads on die and press and resultant load spikes will be less likely to exceed the rated press capacity.

2.C.7.g. Key Points

- Press loads are increased for AHSS steels primarily because of their increased work hardening.
- More important than press force is the press energy required to continue production. The required energy can be visualized as area under the true stress–true strain curves.
- High forming loads and energy requirements in a typical hat-profile cross member with a strengthening bead in the channel base are due to the final embossing segment of the punch stroke compared to the pure drawing segment.
- DP 350/600 requires about twice the energy to form hat-profile cross member than the same cross member formed from Mild steel.
- While several punch force approximation techniques can be used for AHSS, the recommended procedure is computerized forming-process development.

2.C.8. Lubrication

Lubrication is an important input to almost every sheet metal forming operation. The lubricants have the following interactions with the forming process:

1. Control metal flow from the binder.
2. Distribute strain over the punch.
3. Maximize/minimize the growth of strain gradients (deformation localization).
4. Reduce surface damage (galling and scoring).
5. Remove heat from the deformation zone.
6. Change the influence of surface coatings.

All these effects become more important as the strength of the sheet metal increases. Therefore, special attention to lubrication is required when considering AHSS.

Higher strength steels (both conventional and AHSS) have less capacity for stretch (less work hardening or n-value) over the punch or pullover plug to generate the required length of line. As the steel strength increases, more metal must flow from the binder into the die to compensate for the loss of length of line for a required part depth. Tensile stresses are applied to the metal under the binder in the radial direction (perpendicular to the die radius) to pull the metal towards the die radius. Compressive stresses can form in the circumferential direction (parallel to the die radius) as the blank reduces its circumferential length. While this compression usually happens in box corners, it also can happen in sidewall features that shorten the length of line while moving into the part. Metal flowing uncontrolled into a sidewall also can generate compressive circumferential stresses. These compressive stresses tend to buckle the binder metal rather than uniformly increase the local thickness. This buckling is following the law of least energy-forming mode in sheet metal forming. Less energy is required to form a local hinge (a buckle) using only few elements of the sheet metal compared to uniformly in-plane compressing the metal to generate an increase in thickness for a large number of elements.

Weight reduction programs use higher strength steels to reduce the sheet metal thickness. The thinner sheet metal is more prone to buckling than thicker steels. Therefore, part designs utilizing AHSS with thinner sheets can require significantly increased blankholder forces to flatten buckles that form. Since restraining force is a function of the coefficient of friction (C.O.F.) times the blankholder force, the restraining force increases and metal flow decreases. Counter measures include an improvement in lubrication with a lower C.O.F. or other process change.

Deforming higher strength steels (especially AHSS) requires more energy. The relative energy increase required to form a DP 350/600 versus an HSLA 350/450 is available in Figure 2-63. At any given value of strain, a vertical line is drawn. The energy required to deform each steel is the area under their respective true stress/true strain curves. Higher forming energy causes both the part and the die to increase in temperature. Lubricant viscosity decreases – usually with corresponding increase in C.O.F. Lubricant breakdown may occur causing first galling and then scoring of the sheet metal and dies. All these events increase blankholder-restraining force and defeat the goal of more metal flowing into the die. Draw beads in the binder area further complicate the problem. Likewise, increasing the number of parts per minute increases the amount of heat generated with a corresponding increase in sheet metal and die temperature.

One key to solving the heat problem when forming higher strength steels is application of a better lubricant. The chemistries of these better lubricants are less prone to viscosity changes and lubricant breakdown. Water-based lubricants disperse more heat than oil-based lubricants. Some parts may require tunnels drilled inside the tooling for circulating cooling liquids. These tunnels target hot spots (thermal gradients) that tend to localize deformation leading to failures.

Special emphasis by some lubricant companies to provide a stable, low C.O.F. lubricant is the dry (barrier) lubricant. These lubricants (mainly polymer based) completely separate the sheet metal from the die. The dry lube C.O.F. for the same sheet metal and die combination can be 0.03 compared to a good wet lubricant C.O.F. of 0.12 to 0.15. That means doubling the blankholder force to maintain very flat binders for joining purposes will still reduce the binder restraining force by one-half or more. That reduction in binder restraining force now allows much more metal flow into the die that the amount of punch stretching can drop from the FLC red failure zone to well into the green safe zone. The complete separation of sheet metal and die by the barrier lubricant also means isolation of any differences in coating characteristics. In addition, the C.O.F. tends to be temperature insensitive, resulting in a more robust forming system. Finally, a known and constant C.O.F. over the entire stamping greatly improves the accuracy of Computer Forming-Process Development (computerized die tryout).

Key Points

- Lubrication helps control metal flow from the binder towards the die radius and into the part. Because many high strength parts have less stretch over the punch, different lubricant characteristics must enable additional metal flow in the binder.
- Increased metal strength and reduced sheet thickness for weight reduction require greater hold down forces. Maintaining metal flow in the binder requires a robust lubricant with a lower coefficient of friction.
- The increased energy to form many AHSS causes both part and die to increase in temperature. Increased temperature usually causes reduced lubricant viscosity and even lubricant breakdown resulting in galling and scoring.
- The dry barrier lubricants have several characteristics capable of reducing forming problems when making parts with AHSS.

2.C.9. Multiple Stage Forming

2.C.9.a. General Recommendations

1. If possible, form all mating areas in the first stage of a forming process and avoid reworking the same area in the next stages.
2. Design stamping processes so the number of forming stages is minimized.
3. Address potential springback issues as early as possible in the product design stage (design for springback):
   - Avoid right or acute angles.
   - Use larger open wall angles.
   - Avoid large transition radii between two walls.
   - Use open-end stamping (Figure 2-71) in preference to a close-end stamping.

Multiple stage forming is recommended for stamping rails or other parts with hat-like cross-section, which consist of right angles. In this case, using a two-stage forming process gives much better geometry control than a single stage process. An example of such a process is shown in the figure below.

In the first operation (Figure 2-71), all 90-degree radii and mating surfaces are formed using “gull-wing” processes with overbending to compensate for springback (note that a large radius is used in the top of the hat area). In the second stage, the top of the rail is flattened. Certain cases may require an overbending of the flat top section.

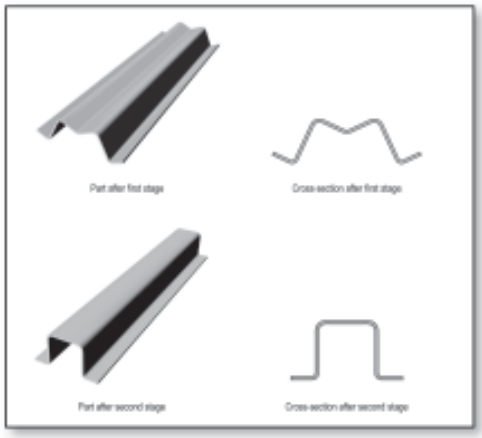


Figure 2-71 - Two-stage forming to achieve a hat section with small radii.[R-1]

Multiple forming is also recommended for parts that consist of small geometrical features of severe geometry that can be formed only in the re-strike operation.

A part that has a variable cross section in combination with small geometrical features may need a coining operation in the second or last stage of the forming process. This is the only way to control the geometry.

2.C.9.b. Key Points

- Minimize the number of multiple forming stages.
- Address springback issues at the earliest possible stage.
- Multiple stage forming can assist in producing a square channel cross section.

2.C.10. In-service Requirements

The microstructure of DP and TRIP steels increase the sheet metal forming capability, but also improve energy absorption in both a crash environment and fatigue life.

2.C.10.a. Crash Management

DP and TRIP steels with ferrite as a major phase show higher energy absorbing property than conventional high-strength steels, particularly after pre-deformation and paint baking treatments. Two key features contribute to this high energy-absorbing property: high work hardening rate and large bake hardening (BH) effect.

The relatively high work-hardening rate, exhibited by DP and TRIP steels, leads to a higher ultimate tensile strength than that exhibited by conventional HSS of similar yield strength. This provides for a larger area under the true stress-strain curve, and results in greater energy absorption when deformed in a crash event to the same degree as conventional steels. The high work hardening rate also causes DP and TRIP steels to work harden during forming processes to higher in-panel strength than similar YS HSS, further increasing the area under the stress-strain curve and crash energy absorption. Finally, the high work-hardening rate better distributes strain during crash deformation, providing for more stable, predictable axial crush that is crucial for maximizing energy absorption during a front or rear crash event.

The relatively large BH effect also increases the energy absorption of DP and TRIP steels by further increasing the area under the stress-strain curve. The BH effect adds to the work hardening imparted by the forming operation. Conventional HSS do not exhibit a strong BH effect and therefore do not benefit from this strengthening mechanism.

Figure 2-72 illustrates the difference in energy absorption between DP and TRIP steels as a function of their static (traditional tensile test speed) yield strength.

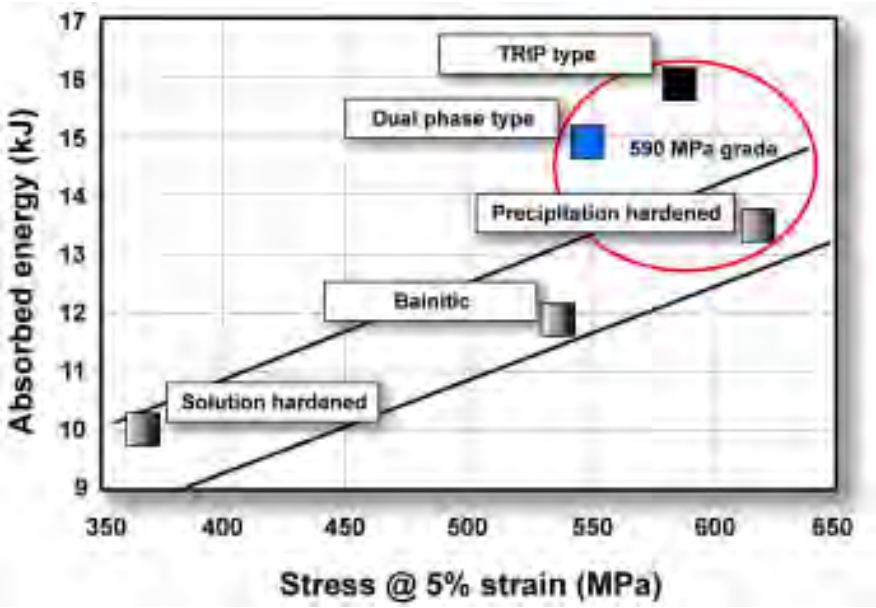


Figure 2-72 - Absorbed energy for square tube as function of static yield strength.[T-2]

Figure 2-73 shows calculated absorbed energy plotted against total elongation for a square tube component. The absorbed energy remains constant for the DP and TRIP steels but the increase in total elongation allows for formation into complex shapes. For a given crash-critical component, the higher elongations of DP and TRIP steels do not generally increase energy absorption compared to conventional HSS if all materials under consideration have sufficient elongation to accommodate the required crash deformation. In some applications, the DP and TRIP grades could increase energy absorption over that of a conventional HSS if the conventional steel does not have sufficient ductility to accommodate the required crash deformation and splits rather than fully completing the crush event. In the latter case, substituting DP or TRIP steel, with sufficient ductility to withstand full crash deformation, will improve energy absorption by restoring stable crush and permitting more material to absorb crash energy.

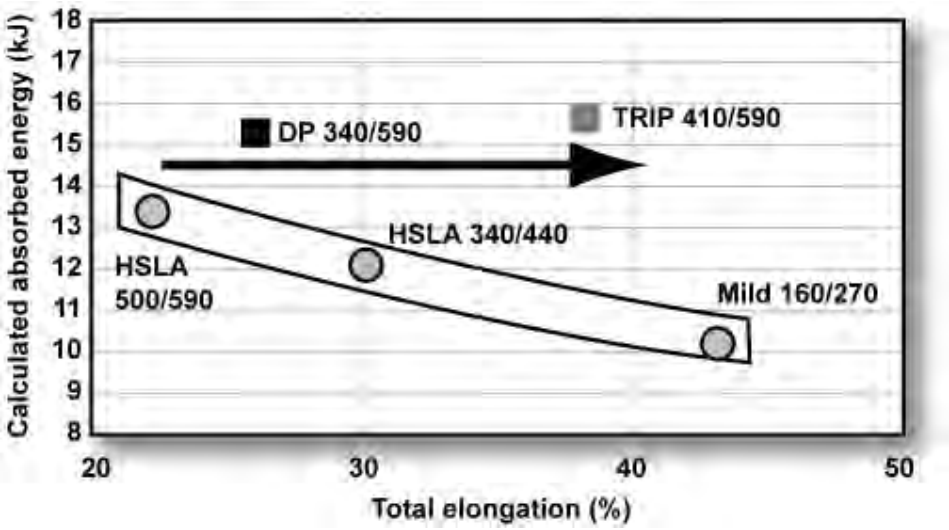


Figure 2-73 - Calculated absorbed energy for a square tube as a function of total elongation.[T-2]

2.C.10.b. Fatigue

The fatigue strength of DP steels is higher than that of precipitation-hardened steels or fully banitic steels of similar yield strength for many metallurgical reasons. For example, the dispersed fine martensite particles retard the propagation of fatigue cracks. For TRIP steels, the transformation of retained austenite can relax the stress field and introduce a compressive stress that can also improve fatigue strength. Figures 2-74 and 2-75 illustrate the improvements in fatigue capability.

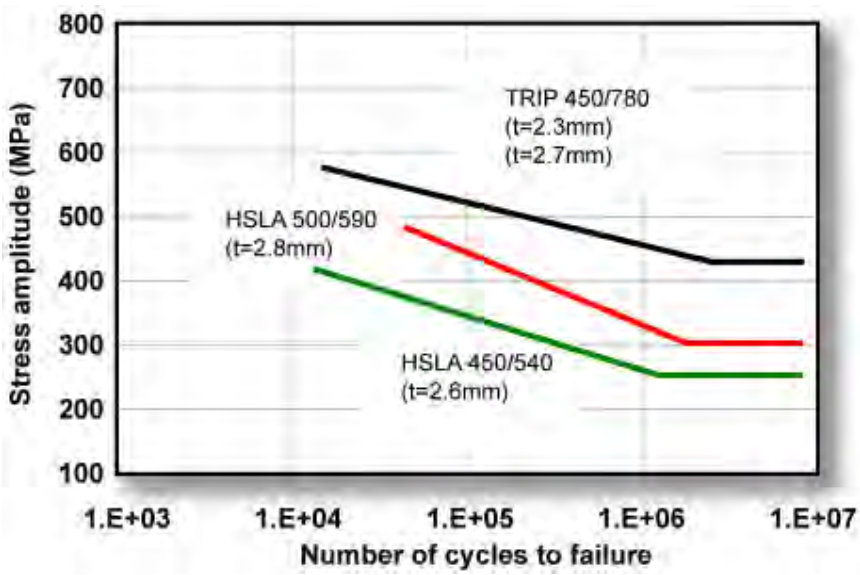


Figure 2-74 - Fatigue characteristics of TRIP 450/780 steel compared to conventional steels.[T-1]

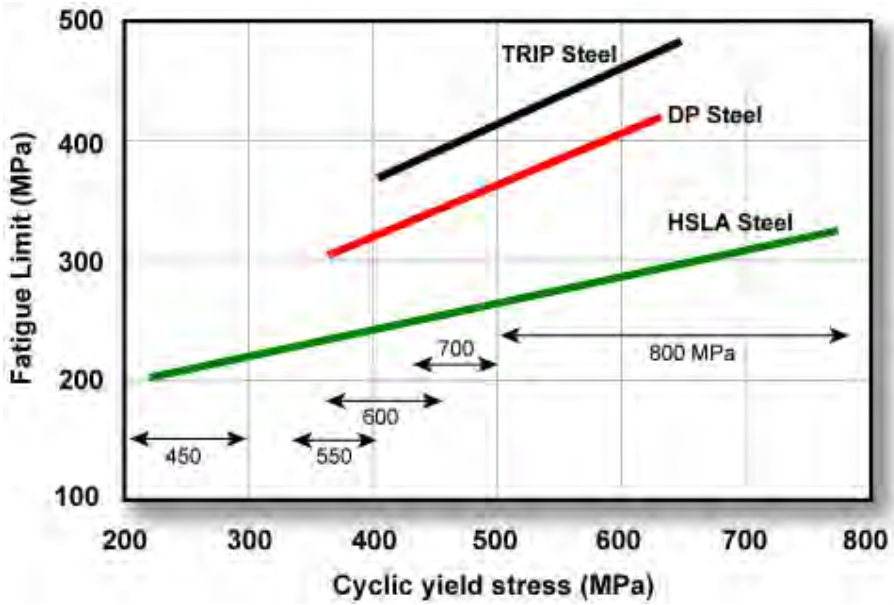


Figure 2-75 - Fatigue limit for AHSS compared to conventional steels.[T-2]

2.C.10.c. Key Points

- DP and TRIP steels have increased energy absorption in a crash event compared to conventional HSS because of their high tensile strength, high work hardening rate, and large BH effect.
- The greater ductility of DP and TRIP steels permit use of higher strength, greater energy absorbing capacity material in a complex geometry that could not be formed from conventional HSS.
- DP and TRIP steels have better fatigue capabilities compared to conventional HSS of similar yield strength.

2.D. Tube Forming

2.D.1. High Frequency Welded Tubes

Welded tubes are commonly produced from flat sheet material by continuous roll forming and a high frequency welding process. These types of tubes are widely used for automotive applications, such as seat structures, cross members, side impact beams, bumpers, engine subframes, trailing arms, and twist beams. Currently AHSS tubes up to grade DP 700/1000 are in commercial use in automotive applications.

Tube manufacturing involves a sequence of processing steps (for example roll forming, welding, calibration, shaping) that influence the mechanical properties of the tube. During the tube manufacture process, both the YS and the UTS are increased while the total elongation is decreased. Subsequently, when manufacturing parts and components, the tubes are then formed by operations such as flaring, flattening, expansion, reduction, die forming, bending and hydroforming. The actual properties of the tube dictate the degree of success to which these techniques can be utilized.

Published data on technical characteristics of tubes made of AHSS is limited. For example, the ULSAB-AVC programme deals only with those tubes and dimensions applied for the actual body structure (Table 2-3).

Table 2-3- Examples of properties for as-shipped straight tubes from ULSAB-AVC project.[I-1]

Steel Grade	YS (MPa)	UTS (MPa)	Tot. EL (%)*
MS 950/1200	1150	1200	5-7
DP 500/800	600	800	16-22
DP 280/600	450	600	27-30

YS and UTS are minimum values, Tot. EL is typical value
Total EL % (ASTM A50 or A80)

The earlier ULSAC study resulted in design and manufacturing of demonstration hardware, which included AHSS tubes made of DP 500/800 material. The ULSAC Engineering Report provides the actual technical characteristics of those two tube dimensions used in the study: 55x30x1.5mm and Ø 34x1.0mm (see http://www.worldautosteel.org/projects/ulsac.aspx for more information).

The work hardening, which takes place during the tube manufacturing process, increases the YS and makes the welded AHSS tubes appropriate as a structural material. Mechanical properties of welded AHSS tubes (Figure 2-76) show welded AHSS tubes provide excellent engineering properties.

In comparison with HSLA steel tubes, the AHSS tubes offer an improved combination of strength, formability, and good weldability. AHSS tubes are suitable for structures and offer competitive advantage through high-energy absorption, high strength, low weight, and cost efficient manufacturing.

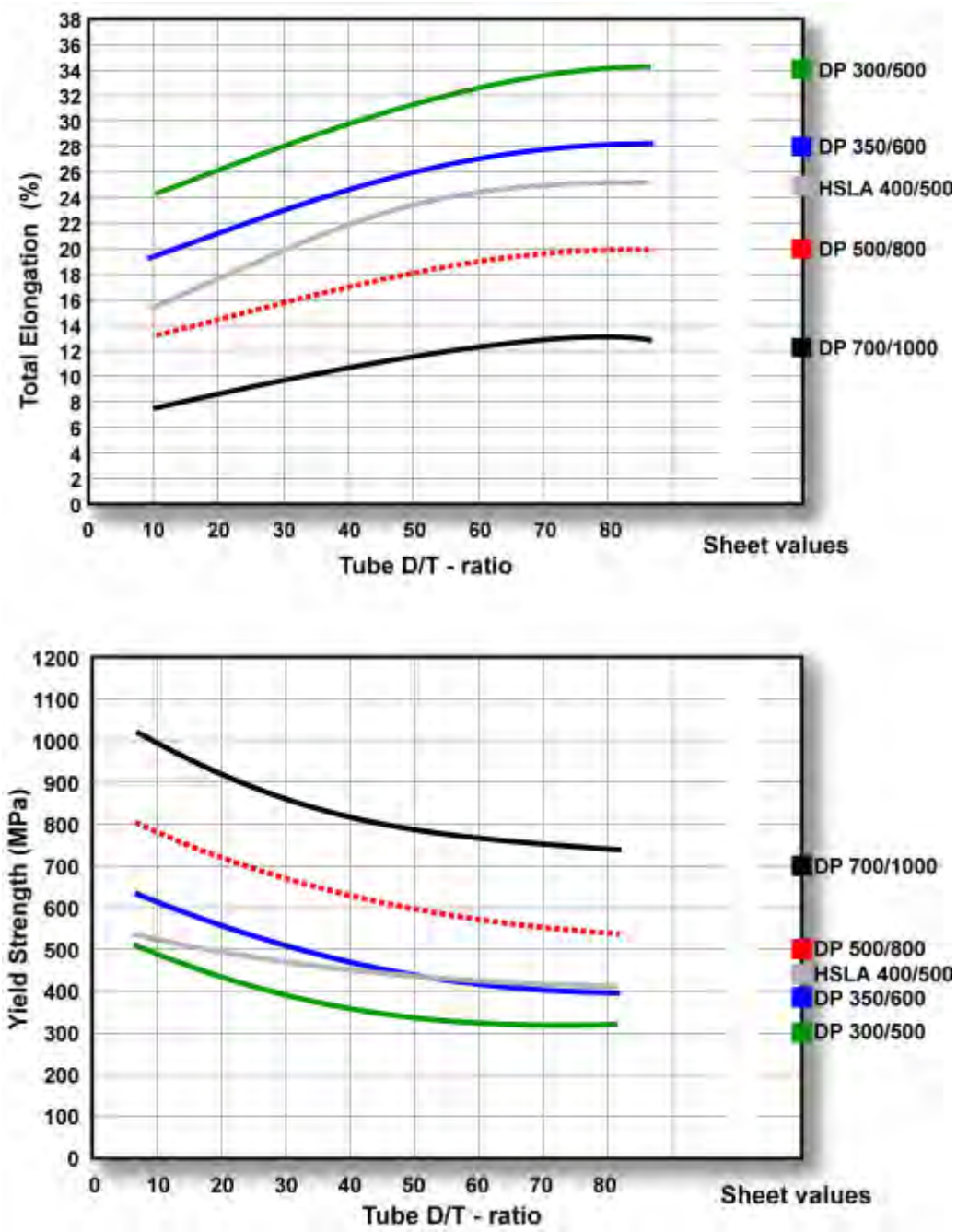


Figure 2-76 - Anticipated Total Elongation and Yield Strength of AHSS tubes.[R-1]

The degree of work hardening, and consequently the formability of the tube, depends both on the steel grade and the tube diameter/thickness ratio (D/T) as shown in Figure 2-76. Depending on the degree of work hardening, the formability of tubular materials is reduced compared to the as-produced sheet material.

Bending AHSS tubes follows the same laws that apply to ordinary steel tubes. One method to evaluate the formability of a tube is the minimum bend radius, which utilizes the total elongation (A_5) defined with proportional test specimen by tensile test for the actual steel grade and tube diameter.

The minimum Centerline Radius (CLR) is defined as:

$$CLR = \mathbf{50} \times \frac{D}{A_5}$$

Computerized forming-process development utilizes the actual true stress-true strain curve, which is measured for the actual steel grade and tube diameter. Figure 2-77 contains examples of true stress-true strain curves for AHSS tubes.

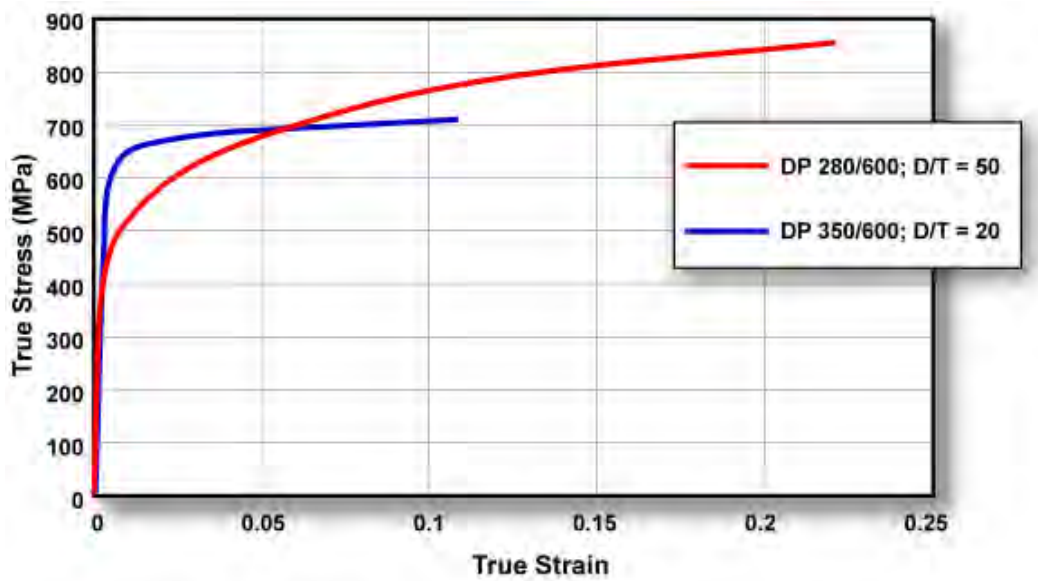


Figure 2-77 - Examples of true stress-true strain curves for AHSS tubes.[R-1]

However, it is important to note that the bending behaviour of tube depends on both the tubular material and the bending technique. The weld seam is also an area of non-uniformity in the tubular cross section. Thus, the weld seam influences the forming behaviour of welded tubes. The first recommended procedure is to locate the weld area in a neutral position during the bending operation.

The characteristics of the weld depend on the actual steel sheet parameters (that is chemistry, microstructure, strength) and the set-up of the tube manufacturing process. The characteristics of the high frequency welds in DP steel tubes are discussed in more detail in Section 3 – 3.B.2.

Figures 2-78 and 2-79 provide examples of the forming of AHSS tubes.

Figure 2-78 - Hydroformed Engine Cradle made from welded DP 280/600 tube with YS ≈ 540 N/mm^2; TS ≈ 710 N/mm^2; Total Elongation ≈ 34%. Draw bending, Centerline Bending Radius = 1.6 x D, Bending Angle > 90 Degrees.[R-1]

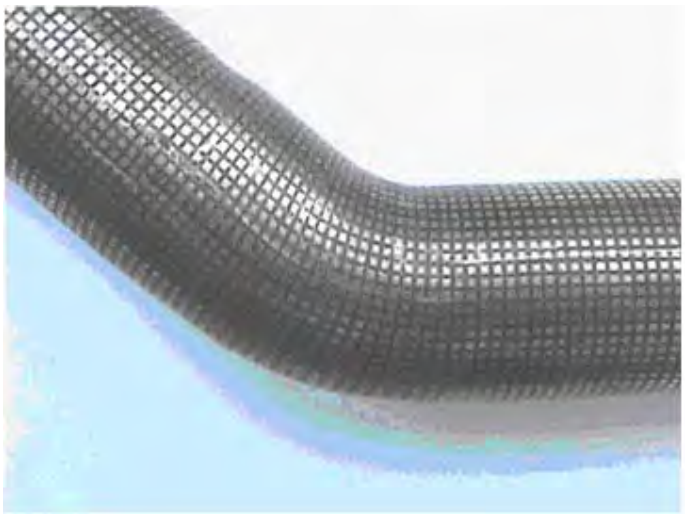


Figure 2-79 - Bending test of welded DP 350/600 tube with YS » 610 N/mm^2; TS ≈ 680 N/mm^2; Total Elongation ≈ 27%. Booster bending, Centerline Bending Radius = 1.5 x D, Bending Angle = 45 Degrees.[R-1]

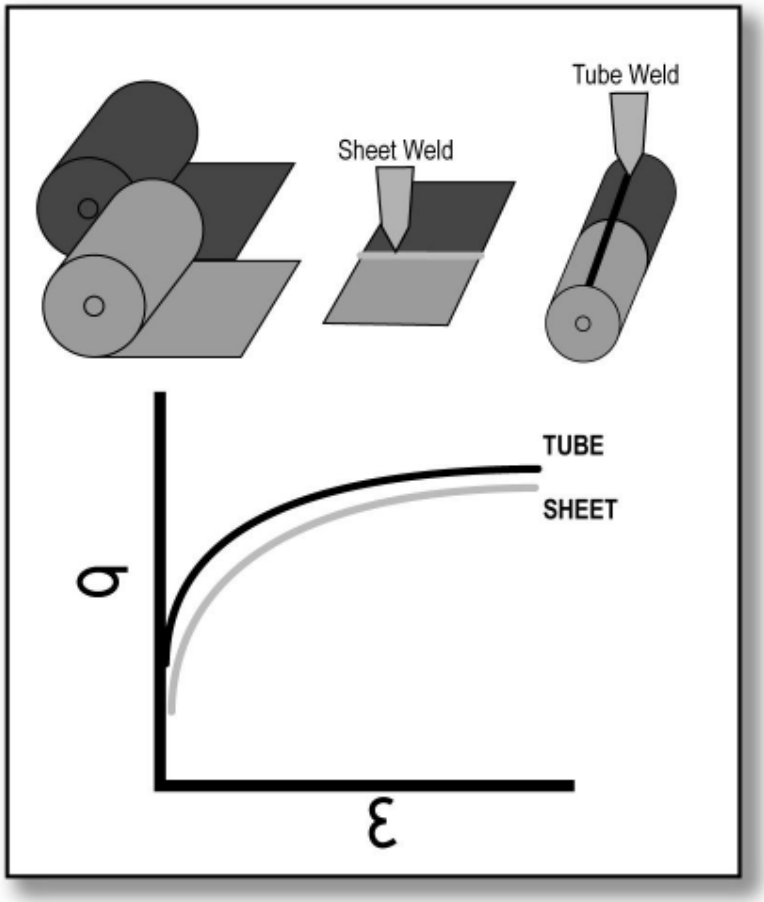
2.D.2. Laser Welded Tailored Tubes

Tube products for chassis applications produced by conventional HF weld process (as previously described) receive their properties during a traditional tube making processes (such as roll-forming and widely used HF-welding).

For body structures, thin-wall tube sections are recommended as a replacement for spot-welded box-shape components. To meet further demands for even thinner gauges (with different metal inner and outer surface coatings in all AHSS grades that are more sensitive to work hardening) an alternative manufacturing process is required to maintain the sheet metal properties in the as-rolled sheet conditions.

Laser welding, used extensively for tailored welded blanks, creates a very narrow weld seam. Sheet metals with dissimilar thickness and/or strengths are successfully used to achieve required weight savings by eliminating additional reinforcement parts. Further weld improvements have been made during the steadily increasing series-production of laser welded blanks.

Part consolidation utilizing hydroforming is one strategy to simultaneously save both cost and weight. With hydroforming technology, the next step in tubular components is to bring the sheet metal into a shape closer to the design of the final component without losing tailored blank features (Figure 2-80).



Figures 2-80 - Mechanical properties of tailored tubes are close to the original metal properties in the sheet condition.[G-1]

The tailored tube production process allows the designer to create complex variations in shape, thickness, strength, and coating. (Figure 2-81). The shape complexity, however, is limited by the steel grades and mechanical properties available.

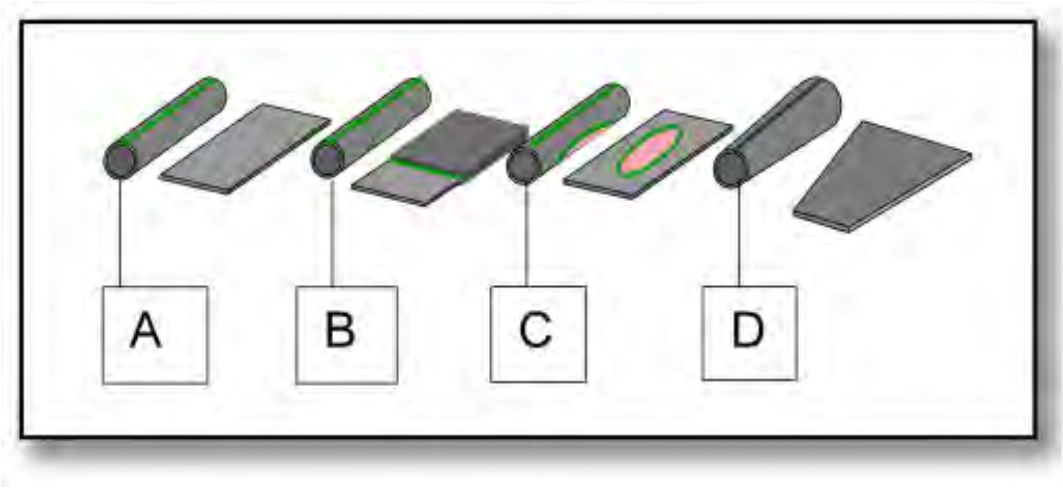


Figure 2-81 - Laser welded, tailored tube examples and required pre-blank shapes.[F-1]
A) 1-piece cylindrical tube
B) 2-piece tailored tube
C) Patchwork tube
D) 1-piece conical tube

Conical tailored tubes, designed for front rail applications, with optimized lightweight and crash management are one opportunity to cope with auto body-frame architecture issues. In frontal crash and side impacts the load paths have a key importance on the body design as they have a major bearing on the configuration of the structural members and joints. Figure 2-82 is an example of a front-rail hydroformed prototype. The conical tailored tubes for this purpose take advantage of the high work hardening potential of TRIP steel.

Figure 2-82- Front-rail prototype based on a conical tube having 40 mm end to end difference in diameter.[F-2]

2.D.3. Key Points

- Due to the cold working generated during tube forming, the formability of the tube is reduced compared to the as-received sheet.
- The work hardening during tube forming increases the YS and TS, thereby allowing the tube to be a structural member.
- Laser welded tubes create a very narrow weld seam.
- The weld seam should be located at the neutral axis of the tube, whenever possible during the bending operation.

2.E. Hydroforming (Tubes)

2.E.1. Pre-Form Bending

As discussed in the previous section, AHSS will initially work harden (increase strength) during the initial tube making process and then continue to work harden more with each forming step in the hydroforming process. For example, tube manufacturing involves a sequence of processing steps - roll forming, welding, calibration, shaping. During the tube manufacturing process, both the YS and the UTS increase while the total elongation and residual stretchability decrease. The same is true during the pre-form bending of the tube. In the area of the tube where the pre-form bending stresses are concentrated, the YS and the UTS will increase in the deformation zone while the total elongation and stretchability decrease locally. When considering production of a hydroformed part, both product and tool designs must account for these increased strengths and reduced formability parameters.

Careful consideration is required to avoid exceeding the available total elongation for bending limits or forming limits - especially for stretchability formations in the finished part that are located in the area of a pre-form bend. Refer to Figure 2-76 for anticipated elongation values for several illustrative high strength steels formed into tubes of various D/T ratios.

The deformation available for the pre-form bend process and the subsequent hydroforming process will depend on the material selected, tube D/T ratio, tube manufacturing process, centreline radius of the pre-form bend, and the included angle of the bend. Referring to figure 2-76 of the previous section, tubes of higher strength AHSS will have limited elongation available. Therefore, analysis of part designs is required to avoid exceeding the various forming limits imposed by the chosen material.

Automotive roof rail sections have incorporated hydroformed parts for several years. The ULSAB-AVC also used this type of construction. More recent vehicles have used much higher strength AHSS to improve roof strength (Figure 2-83).

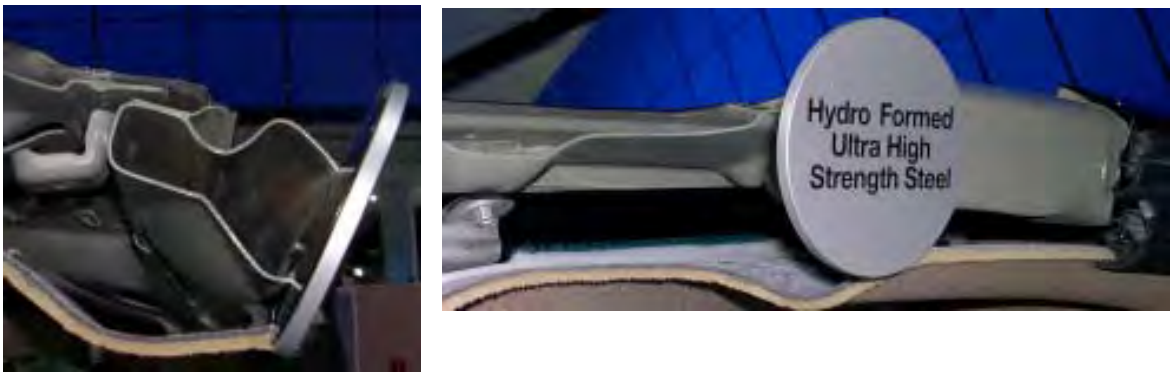


Figure 2-83 – Photos of a North American 2008 truck roof rail using AHSS hydroformed section.[P-1]

2.E.2. Forming

The hydroforming process for tubes usually involves expanding the tube diameter from 3% to 30% depending on the design, materials selected and pressures available for forming. Tube production commonly utilizes one of three basic methods of hydroforming tubes. The first two are low-pressure and high-pressure processes. The low-pressure begins with a tube whose circumference is slightly less than the final circumference of the finished geometry. After placing the tube in an open die, the tube is pressurized. As the die closes, the circumference of the tube changes shape to conform to the closing die. The pressure is sufficient to prevent the tube from buckling during the shape change. The key is very little increase in the circumference to allow high strength and reduced formability metals to achieve tighter radii without failure. This low-pressure process is suitable for tubes made from AHSS.

The second process is high-pressure tube hydroforming. Here the tube is placed in the die and the die is closed. Pressurizing the tube now causes the metal to stretch as the circumference increases to conform to the inner circumference of the die – often with tight radii in corners and product features. Higher strength steels may be unable to expand sufficiently to fill the die geometry or create small radii without failure. However, high pressure could be necessary to obtain the correct geometry with minimum springback or fewer wrinkles compared to low pressure hydroforming.

A third process reduces the severity of circumferential expansion by “end feeding.” Special end pistons push additional material into the die cavity from the tube end to provide more material for higher expansion of the tube circumference. This method of tube circumference expansion involves bi-directional strain. The end feeding is beneficial for hydroforming tubes from AHSS.

Hydroforming AHSS tubes require highly developed forming limit charts that utilize tube D/T, degree of pre-form bend, and final geometrical shape. Currently, these data are limited for AHSS beyond DP steels with a tensile strength greater than 600 MPa. The availability of forming limit charts will improve as new applications develop rapidly. To assist with very early process and die design, computerized forming-process development is an excellent tool for examining the validity of applying different AHSS to potential part designs.

Figures 2-84 and 2-85 illustrate two hydroformed production parts.

Figure 2-84 – This duplicate of Figure 2-78 shows the two potential problem areas (circled) for a hydroformed Engine Cradle made from welded DP 280/600 tube .[R-1]

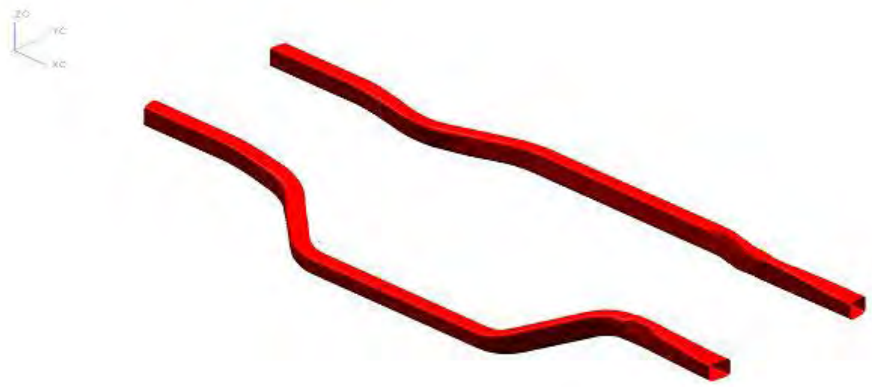


Figure 2-85 - Opal Speedster, Pontiac Solstice and Saturn Sky main body side rail: Tube DIA 132 mm, Gauge 1.8 mm, D/T = 73, Finished length 4070mm, DP 350/600.[A-7]

2.E.3. Post Forming Trimming

For trimming and piercing, the same general cautions utilized for stamped AHSS parts apply to hydroformed AHSS parts. Since AHSS have higher tensile strength than conventional high-strength steels, engineering the trim tools to withstand higher loads is a requirement. Proper support for the trim stock during the trim operation also is very important to minimize edge cracking. Laser trimming, which is common for hydroformed parts, is still an excellent choice. However, evaluating the hardening effects of the laser beam on the trimmed edge is required.

2.E.4. Design Considerations

Today, hydroformed parts are widely used for automotive applications, such as seat structures, cross members, side impact beams, bumpers, engine subframes, trailing arms, roof rails and twist beams. Currently, AHSS tubes up to grade DP 700/1000 are in commercial use in automotive applications. In general, the same design guidelines that support hydroforming of conventional steels apply to AHSS. However, additional attention to the available elongation for forming and part function is required as a part design and manufacturing processes are developed.

2.E.5. Key Points

- Tube hydroforming is a current production process for making numerous structural parts.
- Those AHSS tubes with higher yield and tensile strengths but lower total elongations and stretchability limits will limit some hydroformed tube designs.
- The total summation of forming deformation is required from all stages of product development, which includes creating the initial tube, pre-bending, hydraulic circumferential expansion, and forming of local features.
- AHSS tube trimming and piercing have similar cautions as AHSS stamped part trimming and piercing.

Section 1 General Description of AHSS

Section 1 - General Description of AHSS

About a decade ago, a consortium of thirty-five steel companies worldwide undertook a massive programme to design, build, and test an UltraLight Steel Auto Body (ULSAB).[W-1]. ULSAB proved to be lightweight, structurally sound, safe, executable and affordable. One of the major contributors to the success of the ULSAB was a group of new steel types and grades called Advanced High Strength Steels (AHSS). The AHSS family of unique microstructures typified the steel industry's response to the demand for improved materials that utilize proven production methods. Table 1-1 illustrates a range of steel grades used in the Advanced Vehicle Concept (ULSAB-AVC) programme.

Table 1-1 - Examples of Steel Grade Properties from ULSAB-AVC.[W-1]

Steel Grade	YS (MPa)	UTS (MPa)	Tot. EL (%)
HSLA 350/450	350	450	23-27
DP 300/500	300	500	30-34
DP 350/600	350	600	24-30
TRIP 450/800	450	800	26-32
DP 500/800	500	800	14-20
CP 700/800	700	800	10-15
DP 700/1000	700	1000	12-17
MS 1250/1520	1250	1520	4-6

YS and UTS are minimum values
Tot. EL (Total Elongation) range shows typical values for a broad range of sheet thicknesses and gauge lengths.

The main reason to utilize AHSS is their better performance in crash energy management, which allows one to down gauge with AHSS. In addition, these engineered AHSS address the automotive industry's need for steels with higher strength and enhanced formability. The DP (Dual phase) and TRIP (Transformation induced plasticity) steels may provide additional stretchability (but not bendability) compared to conventional steels such as HSLA steels within the same strength range. The CP (Complex phase) and MS (Martensitic) steels extend the strength range while maintaining the same formability.

While the ULSAB proved these AHSS provided a major benefit to the automotive industry, these steels reacted differently from traditional higher strength steels in forming and assembly. Worldwide working groups within the WorldAutoSteel organization created the AHSS Application Guidelines to explain how and why AHSS steels were different from traditional higher strength steels in terms of press-forming, fabrication, and joining processes for automotive underbody, structural, and body panels designed for higher strength steels. This Version 4 document provides in-depth information on a wide range of topics. A companion document published by the Auto/Steel Partnership[A-6] details AHSS part design and die tryout experiences with actual part case studies.

Over the years since ULSAB, the successes of AHSS have motivated steel companies to continue research on both new types and grades of AHSS and then bring these new steels to production. In 2008, WorldAutoSteel began yet another programme called Future Steel Vehicle[W-2]. This programme will benefit from the availability these new AHSS. Table 1-2 shows how the menu of steels has grown significantly.

Table 1-2 – Steel grades available for Future Steel Vehicle.[W-2]
sorted by yield strength

Steel Grade	YS (MPa)	UTS (MPa)	Tot. EL (%)
Mild 140/270	140	270	42-48
BH 210/340	210	340	35-41
BH 260/370	260	370	32-36
IF 260/410	260	410	34-48
BH 280/400	280	400	30-34
IF 300/420	300	420	29-36
DP300/500	300	500	30-34
FB 330/450	330	450	29-33
HSLA 350/450	350	450	23-27
DP 350/600	350	600	24-30
TRIP 350/600	350	600	29-33
DP 400/700	400	700	19-25
TRIP 400/700	400	700	24-28
HSLA 420/500	420	500	22-26
FB 450/600	450	600	18-26
TRIP 450/800	450	800	26-32
TWIP 450/1000	450	1000	50-54
HSLA 490/600	490	600	20-25
CP 500/800	500	800	10-14
DP 500/800	500	800	14-20
HSLA 550/650	550	650	19-23
DP 700/1000	700	1000	12-17
CP 800/1000	800	1000	8-13
MS 950/1200	950	1200	5-7
CP 1000/1200	1000	1200	8-10
HF 1050/1500 (22MnB5)			
- *Conventional Forming*	340	480	23 -27
- *Heat Treated Post Forming*	1050	1500	5-7
MS 1150/1400	1150	1400	4-7
MS 1250/1520	1250	1520	3-6

YS and UTS are minimum values

Tot. EL (Total Elongation) range shows typical values for a broad range of sheet thicknesses and gauge lengths.

It is important to note that different automotive companies throughout the world have adopted different specification criteria and that steel companies have different production capabilities and commercial availability. For example, properties of hot-rolled steels can differ from cold-rolled steels. Even coating processes (Hot-Dipped Galvanize versus Hot-Dipped Galvanneal) subject the base metal to different thermal cycles that affect final properties. Therefore, the typical mechanical properties shown above simply illustrate the broad range of AHSS grades that may be available worldwide. In addition, regional test procedures will cause a systematic variation in some properties measured on the same steel sample. One example is total elongation, where measurement gauge length can be 50-mm or 80-mm plus different gauge widths depending on the worldwide region in which the test is conducted. In addition, minimum values can be defined relative to either the rolling direction or transverse direction. Therefore, communication directly with individual steel companies is imperative to determine grade availability along with specific test procedures, associated parameters, and steel properties. The following list of information is important when determining the suitability of a steel type and grade for any given part:

- Hot-rolled, cold-rolled, and coating availability
- Thickness and width capabilities
- Chemical composition specifications
- Mechanical properties and ranges
- Joining requirements

1.A. Definitions

Automotive steels can be classified in several different ways. One is a metallurgical designation. Common designations include low-strength steels (interstitial-free and mild steels); conventional HSS (carbon-manganese, bake hardenable, high-strength interstitial-free, and high-strength, low-alloy steels); and the newer types of AHSS (dual phase, transformation-induced plasticity, complex phase, and martensitic steels). Additional higher strength steels for the automotive market include ferritic-bainitic, twinning-induced plasticity, hot-formed, and post-forming heat-treated steels.

A second classification method important to part designers is strength of the steel. Therefore, this document will use the general terms HSS and AHSS to designate all higher strength steels. In contrast, much of the current literature uses narrowly defined ranges to categorize different steel strength levels. One such system defines High-Strength Steels (HSS) as yield strengths from 210 to 550 MPa and tensile strengths from 270–700 MPa, while Ultra-High-Strength Steels (UHSS) steels have yield strengths greater than 550 MPa and tensile strengths greater than 700 MPa. These arbitrary ranges suggest discontinuous changes in formability when moving from one category to another. However, data show property changes are a continuum across the entire span of steel strengths. In addition, many steel types have a wide range of grades covering two or more strength ranges.

A third classification method presents various mechanical properties or forming parameters of different steels, such as total elongation, work hardening exponent n, or hole expansion ratio λ. As an example, Figure 1-1 compares total elongations – a steel property related to formability – for the different metallurgical types of steel. Figure 1-1A shows the lower strength steels in dark grey and the traditional HSS steels in light grey. Some of the early AHSS steel ellipses have colour instead of shades of gray. Figure 1-1B highlights some of the newer higher strength steels for the automotive market. Figures 1-1A and 1-1B illustrate only the relative comparison of different steel grades – not specific property ranges of each type.

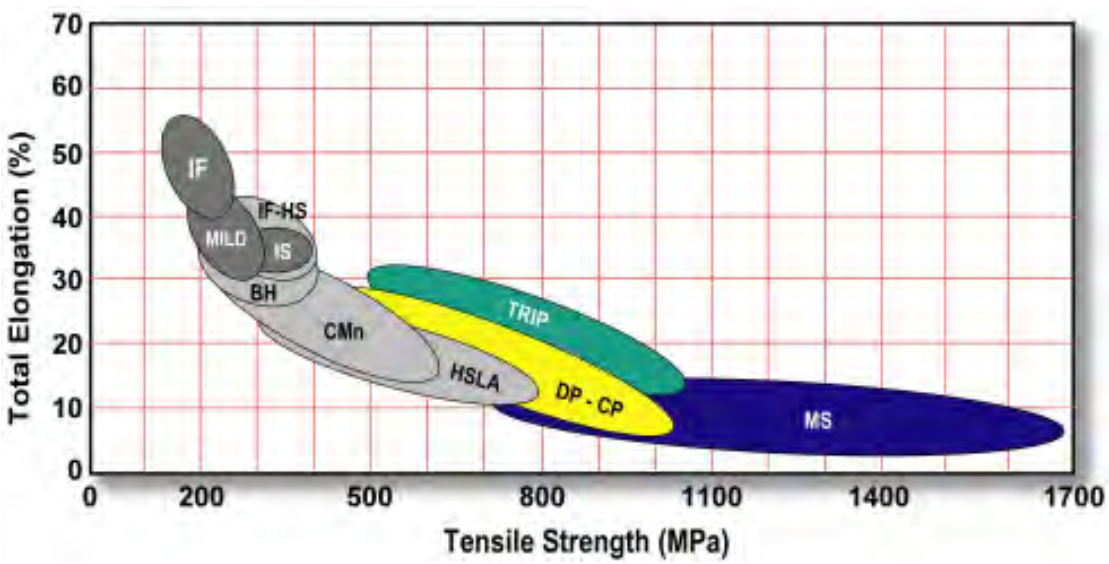


Figure 1-1A - Schematic of AHSS steels (shown in colour) compared to low strength steels (dark grey) and traditional HSS (light grey).[W-1]

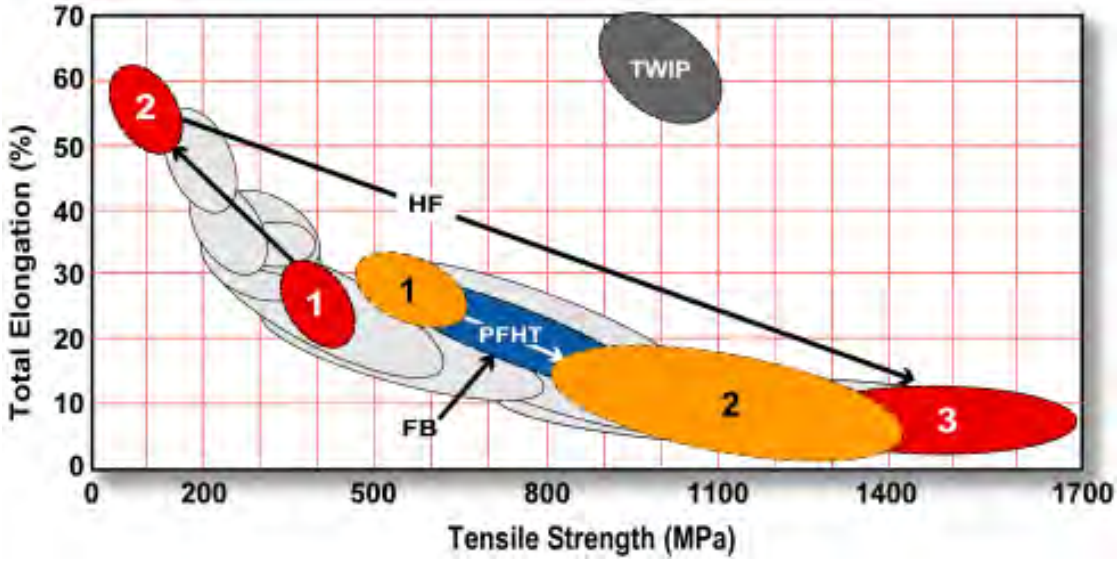


Figure 1-1B – Schematic of newer higher strength steels utilizing unique chemistries, processing, and microstructure to gain specific properties and forming characteristics.[W-2]

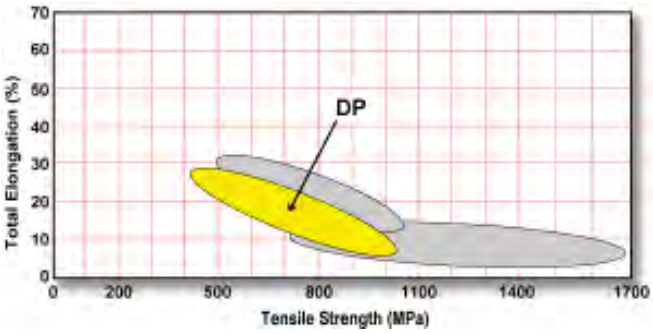
The principal difference between conventional HSS and AHSS is their microstructure. Conventional HSS are single-phase ferritic steels. AHSS are primarily steels with a microstructure containing a phase other than ferrite, pearlite - for example martensite, bainite, austenite, and/or retained austenite in quantities sufficient to produce unique mechanical properties. Some types of AHSS have a higher strain hardening capacity resulting in a strength-ductility balance superior to conventional steels. Other types have ultra-high yield and tensile strengths and show a bake hardening behaviour.

Since the terminology used to classify steel products varies considerably throughout the world, this document uses a combination of methods to define the steels. Each steel grade is identified by metallurgical type, minimum yield strength (in MPa), and minimum tensile strength (in MPa). As an example, DP 500/800 means a dual phase steel type with 500 MPa minimum yield strength and 800 MPa minimum ultimate tensile strength. The ULSAB-AVC programme [W-1] used this classification system.

1.B. Metallurgy of AHSS

Manufacturers and users of steel products generally understand the fundamental metallurgy of conventional low- and high-strength steels. Section 1.C provides a brief description of common steel types. Since the metallurgy and processing of AHSS grades are somewhat novel compared to conventional steels, they are described here to provide a baseline understanding of how their remarkable mechanical properties evolve from their unique processing and structure. All AHSS are produced by controlling the cooling rate from the austenite or austenite plus ferrite phase, either on the runout table of the hot mill (for hot-rolled products) or in the cooling section of the continuous annealing furnace (continuously annealed or hot-dip coated products).

1.B.1. Dual Phase (DP) Steel



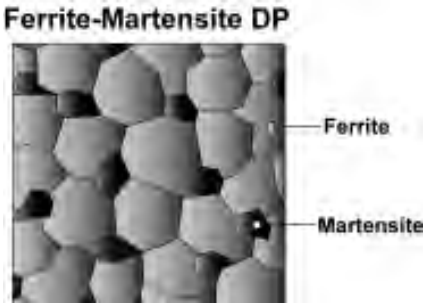


Figure 1-2 - Schematic shows islands of martensite in a matrix of ferrite.

DP steels consist of a ferritic matrix containing a hard martensitic second phase in the form of islands. Increasing the volume fraction of hard second phases generally increases the strength. DP (ferrite plus martensite) steels are produced by controlled cooling from the austenite phase (in hot-rolled products) or from the two-phase ferrite plus austenite phase (for continuously annealed cold-rolled and hot-dip coated products) to transform some austenite to ferrite before a rapid cooling transforms the remaining austenite to martensite.

Depending on the composition and process route, hot-rolled steels requiring enhanced capability to resist stretching on a blanked edge (as typically measured by hole expansion capacity) can have a microstructure containing significant quantities of bainite.

Figure 1-2 shows a schematic microstructure of DP steel, which contains ferrite plus islands of martensite. The soft ferrite phase is generally continuous, giving these steels excellent ductility. When these steels deform, strain is concentrated in the lower-strength ferrite phase surrounding the islands of martensite, creating the unique high work-hardening rate exhibited by these steels.

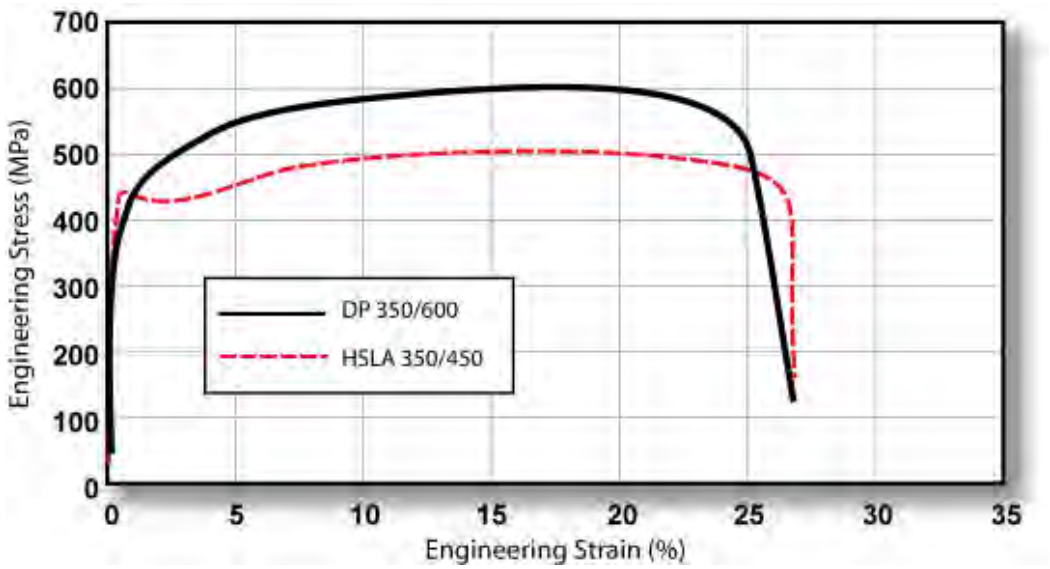


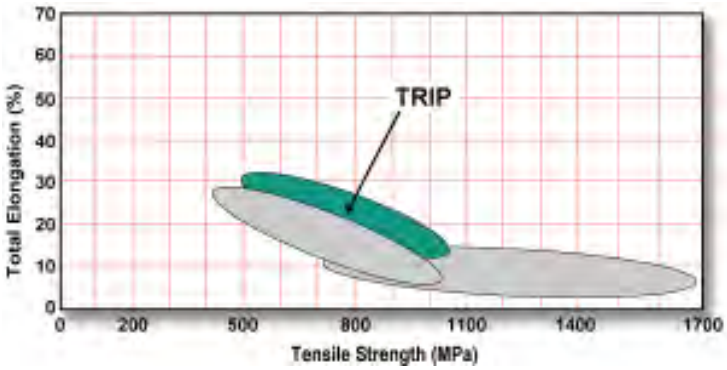
Figure 1-3 - The DP 350/600 with higher TS than the HSLA 350/450.[K-1]

The work hardening rate plus excellent elongation creates DP steels with much higher ultimate tensile strengths than conventional steels of similar yield strength. Figure 1-3 compares the engineering stress-strain curve for HSLA steel to a DP steel curve of similar yield strength. The DP steel exhibits higher initial work hardening rate, higher ultimate tensile strength, and lower YS/TS ratio than the similar yield strength HSLA. Additional engineering and true stress-strain curves for DP steel grades are located in Figure 2-9B.

DP and other AHSS also have a bake hardening effect that is an important benefit compared to conventional higher strength steels. The bake hardening effect is the increase in yield strength resulting from elevated temperature aging (created by the curing temperature of paint bake ovens) after prestraining (generated by the work hardening due to deformation during stamping or other manufacturing process). The extent of the bake hardening effect in AHSS depends on the specific chemistry and thermal histories of the steels. Additional bake hardening information is located in Section 2.C.1.g.

In DP steels, carbon enables the formation of martensite at practical cooling rates by increasing the hardenability of the steel. Manganese, chromium, molybdenum, vanadium, and nickel, added individually or in combination, also help increase hardenability. Carbon also strengthens the martensite as a ferrite solute strengthener, as do silicon and phosphorus. These additions are carefully balanced, not only to produce unique mechanical properties, but also to maintain the generally good resistance spot welding capability. However, when welding the highest strength grade (DP 700/1000) to itself, the spot weldability may require adjustments to the welding practice.

1.B.2. Transformation-Induced Plasticity (TRIP) Steel



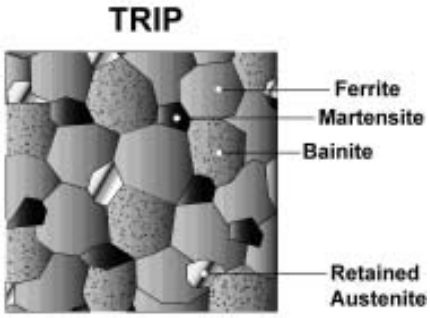


Figure 1-4 – Bainite and retained austenite are additional phases in TRIP steels.

The microstructure of TRIP steels is retained austenite embedded in a primary matrix of ferrite. In addition to a minimum of five volume percent of retained austenite, hard phases such as martensite and bainite are present in varying amounts. TRIP steels typically require the use of an isothermal hold at an intermediate temperature, which produces some bainite. The higher silicon and carbon content of TRIP steels also result in significant volume fractions of retained austenite in the final microstructure. Figure 1-4 shows a schematic of TRIP steel microstructure.

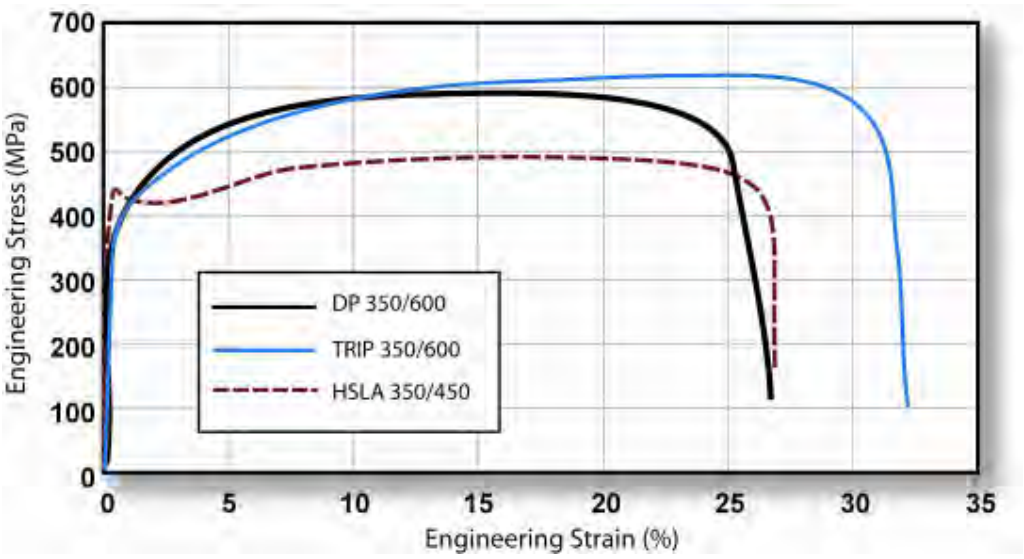


Figure 1-5 - TRIP 350/600 with a greater total elongation than DP 350/600 and HSLA 350/450.[K-1]

During deformation, the dispersion of hard second phases in soft ferrite creates a high work hardening rate, as observed in the DP steels. However, in TRIP steels the retained austenite also progressively transforms to martensite with increasing strain, thereby increasing the work hardening rate at higher strain levels. This is illustrated in Figure 1-5, where the engineering stress-strain behaviour of HSLA, DP and TRIP steels of approximately similar yield strengths are compared. The TRIP steel has a lower initial work hardening rate than the DP steel, but the hardening rate persists at higher strains where work hardening of the DP begins to diminish. Additional engineering and true stress-strain curves for TRIP steel grades are located in Figure 2-9C.

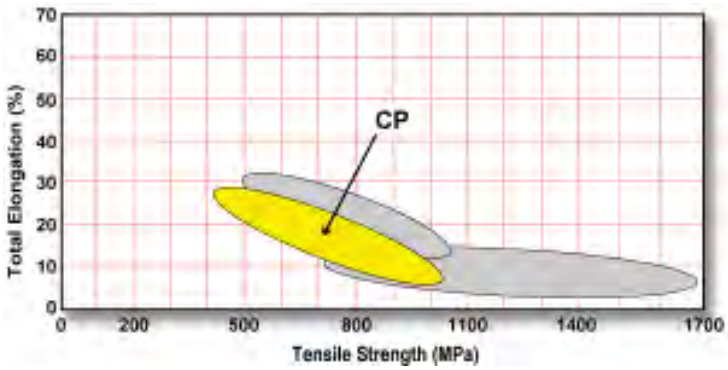
The work hardening rates of TRIP steels are substantially higher than for conventional HSS, providing significant stretch forming. This is particularly useful when designers take advantage of the high work hardening rate (and increased bake hardening effect) to design a part utilizing the as-formed mechanical properties. The high work hardening rate persists to higher strains in TRIP steels, providing a slight advantage over DP in the most severe stretch forming applications.

TRIP steels use higher quantities of carbon than DP steels to obtain sufficient carbon content for stabilizing the retained austenite phase to below ambient temperature. Higher contents of silicon and/or aluminium accelerate the ferrite/bainite formation. Thus, these elements assist in maintaining the necessary carbon content within the retained austenite. Suppressing the carbide precipitation during bainitic transformation appears to be crucial for TRIP steels. Silicon and aluminium are used to avoid carbide precipitation in the bainite region.

The strain level at which retained austenite begins to transform to martensite is controlled by adjusting the carbon content. At lower carbon levels, the retained austenite begins to transform almost immediately upon deformation, increasing the work hardening rate and formability during the stamping process. At higher carbon contents, the retained austenite is more stable and begins to transform only at strain levels beyond those produced during forming. At these carbon levels, the retained austenite persists into the final part. It transforms to martensite during subsequent deformation, such as a crash event.

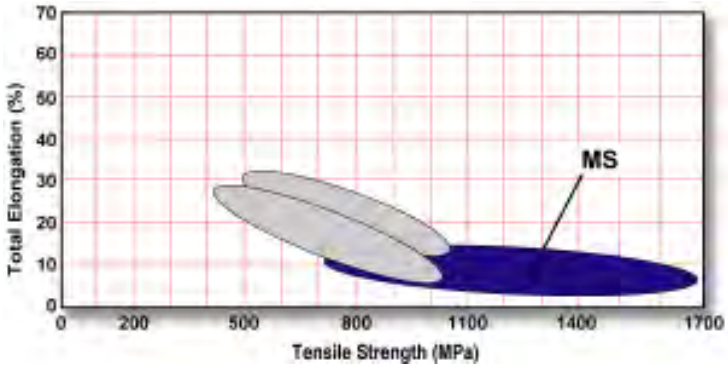
TRIP steels therefore can be engineered or tailored to provide excellent formability for manufacturing complex AHSS parts or exhibit high work hardening during crash deformation for excellent crash energy absorption. The additional alloying requirements of TRIP steels degrade their resistance spot-welding behaviour. This can be addressed somewhat by modification of the welding cycles used (for example, pulsating welding or dilution welding).

1.B.3. Complex Phase (CP) Steel



CP steels typify the transition to steel with very high ultimate tensile strengths. The microstructure of CP steels contains small amounts of martensite, retained austenite and pearlite within the ferrite/bainite matrix. An extreme grain refinement is created by retarded recrystallization or precipitation of microalloying elements like Ti or Cb. In comparison to DP steels, CP steels show significantly higher yield strengths at equal tensile strengths of 800 MPa and greater. CP steels are characterized by high energy absorption and high residual deformation capacity. Engineering and true stress-strain curves for CP steel grades are located in Figure 2-9D.

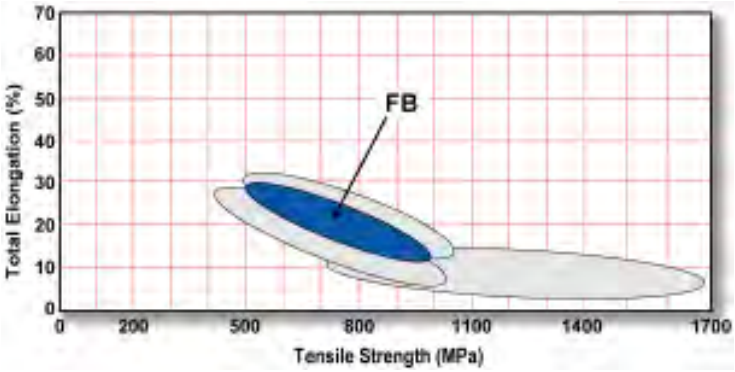
1.B.4. Martensitic (MS) Steel



To create MS steels, the austenite that exists during hot-rolling or annealing is transformed almost entirely to martensite during quenching on the run-out table or in the cooling section of the continuous annealing line. The MS steels are characterized by a martensitic matrix containing small amounts of ferrite and/or bainite. Within the group of multiphase steels, MS steels show the highest tensile strength level. This structure also can be developed with post-forming heat treatment. MS steels provide the highest strengths, up to 1700 MPa ultimate tensile strength. MS steels are often subjected to post-quench tempering to improve ductility, and can provide adequate formability even at extremely high strengths. Engineering and true stress-strain curves for MS steel grades are located in Figure 2-9E.

Adding carbon to MS steels increases hardenability and strengthens the martensite. Manganese, silicon, chromium, molybdenum, boron, vanadium, and nickel are also used in various combinations to increase hardenability. MS steels are produced from the austenite phase by rapid quenching to transform most of the austenite to martensite. CP steels also follow a similar cooling pattern, but the chemistry of MS steel is adjusted to produce less retained austenite and form fine precipitates to strengthen the martensite and bainite phases.

1.B.5. Ferritic-Bainitic (FB) Steel



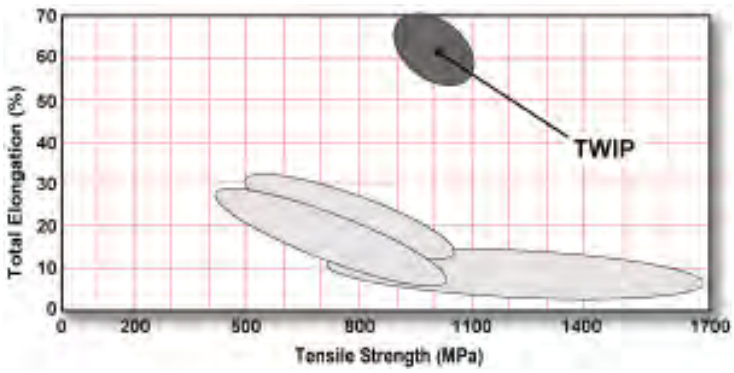
FB steels sometimes are utilized to meet specific customer application requirements defining Stretch Flangeable (SF) or High Hole Expansion (HHE) capabilities for improved edge stretch capability.

FB steels have a microstructure of fine ferrite and bainite. Strengthening is obtained by both grain refinement and second phase hardening with bainite. FB steels are available as hot-rolled products.

The primary advantage of FB steels over HSLA and DP steels is the improved stretchability of sheared edges as measured by the hole expansion test λ. Compared to HSLA steels with the same level of strength, FB steels also have a higher strain hardening exponent (n) and increased total elongation.

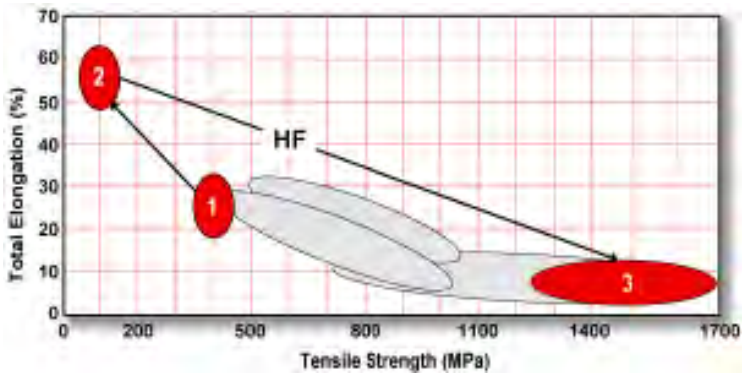
Because of their good weldability, FB steels are considered for tailored blank applications. These steels also are characterized by both good crash performances and good fatigue properties.

1.B.6. Twinning-Induced Plasticity (TWIP) Steel



TWIP steels[C-4] have a high manganese content (17-24%) that causes the steel to be fully austenitic at room temperatures. A large amount of deformation is driven by the formation of deformation twins. This deformation mode leads to the naming of this steel class. The twinning causes a high value of the instantaneous hardening rate (n value) as the microstructure becomes finer and finer. The resultant twin boundaries act like grain boundaries and strengthen the steel. TWIP steels combine extremely high strength with extremely high stretchability. The n value increases to a value of 0.4 at an approximate engineering strain of 30% and then remains constant until both uniform and total elongation reach 50%. The tensile strength is higher than 1000 MPa.

1.B.7. Hot-Formed (HF) Steel



The implementation of press-hardening applications and the utilization of hardenable steels are promising alternatives for optimized part geometries with complex shapes and no springback issues. Boron-based hot-forming steels (between 0.002% and 0.005% boron) have been in use since the 1990s in body-in-white construction. A typical minimum temperature of 850 °C must be maintained during the forming process (austenitization) followed by a cooling rate greater than 50 °C/s to ensure that the desired mechanical properties are achieved.

Two types of press-hardening or hot forming applications are currently available:

1. Direct Hot-Forming
2. Indirect Hot-Forming

During Direct Hot-Forming, all deformation of the blank is done in the high temperature austenitic range followed by quenching. Indirect Hot-Forming preforms the blank at room temperature to a high percentage of the final part shape followed by additional high temperature forming and quenching.

Five process stages with different mechanical properties are important for Direct Hot-Forming:

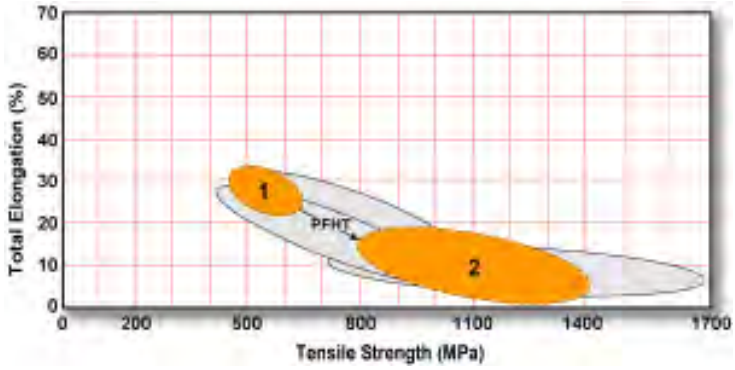
- Stage 1 (ellipse 1): Room temperature blanking: Yield strengths at 340 - 480 MPa, tensile strengths up to 600 MPa, and elongations greater than 18 % must be considered for the design of blanking dies.
- Stage 2 (ellipse 1): Blank heating: The blank is heated to about 850 - 900 °C.
- Stage 3 (ellipse 2): High temperature forming in the die: High elongations (more than 50%) and low strengths (almost a constant 40-90 MPa true stress) at deformation temperatures allow extensive forming at low strengths.
- Stage 4 (ellipse 2): Quenching in the die: Following forming, tensile strengths above 1500 MPa and total elongations of 4 - 8% (martensitic microstructure) develop during part quenching in the die.
- Stage 5 (ellipse 3): Post-forming operations: Because of the very high strength, special processes are necessary when finishing the product (special cutting and trimming devices, etc.).

In contrast, most of the forming during Indirect Hot-Forming is accomplished at room temperature.

- Stage 1 (ellipse 1): Room temperature blanking,
- Stage 2 (ellipse 1): Preforming most of the final part shape at room temperature with a traditional press and die. As with all room temperature forming, as-received sheet metal properties (yield strengths of 340 - 480 MPa, tensile strengths up to 600 MPa, and elongations greater than 18 %) may constrain maximum formability.
- Stage 3 (ellipse 1): Part heating: The part is heated to about 850 - 900 °C.
- Stage 4 (ellipse 2): Final high temperature part forming at low strength and high elongations.
- Stage 5 (ellipse 3): Quenching in the die: Complex parts with tensile strengths above 1500 MPa, total elongations of 6 - 8% (martensitic microstructure) and zero springback develop during quenching in the die.

True stress-strain curves for common boron-based HF steel in both the as-received room temperature condition and after quenching to final strength condition are located in Figure 2-10. Additional information on the hot-forming process is available in Section 2.C.3.e.

1.B.8. Post-Forming Heat-Treatable (PFHT) Steel



Post-forming heat treatment is a general method to develop an alternative higher strength steel. The major issue holding back widespread implementation of HSS typically has been maintaining part geometry during and after the heat treatment process. Fixturing the part and then heating (furnace or induction) and immediate quenching appear to be a solution with production applications. In addition, the stamping is formed at a lower strength (ellipse 1) and then raised to a much higher strength by heat treatment (ellipse 2).

One process is water quenching of inexpensive steels with chemistries that allow in-part strengths between 900 and 1400 MPa tensile strength. In addition, some zinc coatings can survive the heat treating cycle because the time at temperature is very short. The wide assortment of chemistries to meet specific part specifications requires extra special coordination with the steel supplier.

Another process is air-hardening of alloyed tempering steels that feature very good forming properties in the soft-state (deep-drawing properties) and high strength after heat treatment (air-hardening). Apart from direct application as sheet material, air-hardening steels are suitable for tube welding. These tubes are excellent for hydroforming applications. The components can be heat treated in the furnace in a protective gas atmosphere (austenitized) and then hardened and tempered during natural cooling in air or a protective gas. The very good hardenability and resistance to tempering is achieved by adding, in addition to carbon and manganese, other alloying elements such as chrome, molybdenum, vanadium, boron, and titanium. The steel is very easy to weld in both its soft and air-hardened states, as well as in the combination of soft/air-hardened. This steel responds well to coating using standard coating methods (conventional batch galvanizing and high-temperature batch galvanizing).

A third option is in-die quenching. A version of Indirect Hot-Forming (described in 1.B.7.) completes all forming of the part at room temperature, heats the part to about 850 - 900º C, and then uses a water cooled die to quench the part to martensite. This process is called Form Hardening.

1.B.9. Evolving AHSS Types

In response to automotive demands for additional AHSS capabilities, research laboratories in the steel industry and academic institutions continue to search for new types of steel. Figure 1-6 shows one area of current research. The large gray ellipse is one area between the traditional AHSS and the high percentage austenitic-based steels (A) being researched for future steel types. The goal of this research area is improving formability for a given strength range while reducing the cost and welding problems associated with the high percentage austenitic steels. Other examples of these developing steels are ultrafine grain, low density, and high Young's modulus steels.

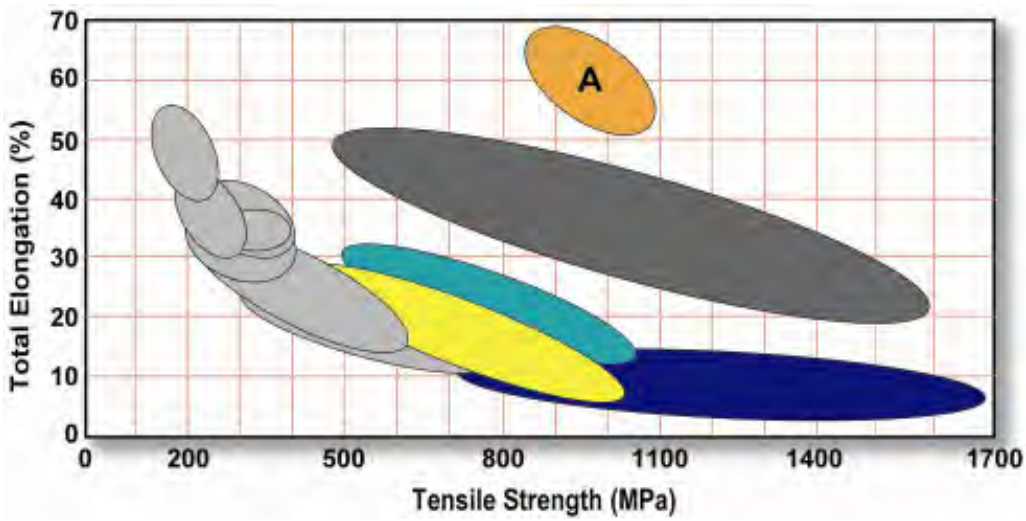


Figure 1-6 - Schematic with large, dark grey ellipse indicating one current area of research for steels with improved properties, reduced cost, and improved weldability.

1.C. Conventional Low- and High-Strength Automotive Sheet Steels

1.C.1. Mild steels

Mild steels have an essentially ferritic microstructure. Drawing Quality (DQ) and Aluminium Killed (AKDQ) steels are examples and often serve as a reference base because of their widespread application and production volume.

1.C.2. Interstitial-free (IF) steels (Low strength and high strength)

IF steels have ultra-low carbon levels designed for low yield strengths and high work hardening exponents. These steels have more stretchability than Mild steels. Some grades of IF steels utilize a combination of elements for solid solution strengthening, precipitation of carbides and/or nitrides, and grain refinement. Another common element added to increase strength is phosphorous (another solid solution strengthener). The higher strength grades of IF steel are widely used for both structural and closure applications.

1.C.3. Bake hardenable (BH) steels

BH steels have a basic ferritic microstructure and solid solution strengthening. A unique feature of these steels is the chemistry and processing designed to keep carbon in solution during steelmaking and then allowing this carbon to come out of solution during paint baking or several weeks at room temperature. This increases the yield strength of the formed part for increased dent resistance.

1.C.4. Isotropic (IS) steels

IS steels have a basic ferritic type of microstructure. The key aspect of these steels is the delta r-value near zero, resulting in minimized earing tendencies.

1.C.5. Carbon-manganese (CM) steels

Higher strength CM steels utilize solid solution strengthening.

1.C.6. High-strength low-alloy (HSLA) steels

This group of steels increase strength primarily by micro-alloying elements contributing to fine carbide precipitation and grain-size refinement.

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