Auto/Steel Partnership

Laboratory Procedure

ASP LP#1.1 (05-2023):

Measuring the Monotonic Properties of Sheet Steel after Pre-Strain and Baking

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Previous Editions:

- None

Changes:

- 1st Version

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Disclaimer

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1.0 Introduction

1.1 Purpose

The purpose of this procedure is to provide a methodology to assess the mechanical properties of sheet steel subjected to controlled pre-strain and baking. The Bake Hardening Index (BHI) is a two-step procedure using a standard longitudinal (rolling direction) tensile-test specimen which is first pre-strained in tension to 2% followed by low temperature baking. The pre-strain is intended to simulate a modest degree of forming strain, while the subsequent baking is intended to simulate a paint-curing or similar treatment. In the production of actual parts, forming strains, and baking treatments can differ from those employed here and, as a result, final properties can differ from the values obtained under these controlled conditions. The BHI enables improved performance modeling of painted automotive formed components by including process forming and thermal history.

1.2 Scope

The procedure consists of process steps to prepare sheet steel coupons for uniaxial tensile testing, is limited to automotive sheet steels and thicknesses for which it has been developed and is a supplement to the BHI procedure described in ASTM A653/653M and DS/EN 10325. The procedure used in both standards applies pre-strain, followed by baking, followed by tensile testing to a standard tensile bar. This method was found to induce out-of-gauge length cracking for advanced high strength steels.

In this procedure, an oversized tensile bar, called KS-1B, is pre-strained. A standard pre-strained tensile bar is then excised from the KS-1B tensile bar, baked and then tensile tested. This helps ensure uniform pre-strain within the tensile bar gauge area and has resulted in more consistent tensile test results.

The procedure includes the preferred method in which coupons are labeled and corresponding test data is curated.

1.3 Abbreviations, Symbols and Designations

A_{P0}	**KS-1B bar gauge area before being pre-strained and excised**
a_{T0}	Tensile bar gauge area before being pre-strained and excised
BH	Bake hardened
BHI	Bake Hardened Index
C	Celsius
MPa	Mega-Pascals
R_{p2}	Stress corresponding to a 2 % plastic pre-strain measured on the test piece
$R_{el.t}$	Lower yield strength measured on the test piece initially pre-strained at 2 % and then heat treated
$R_{p0.2.t}$	0.2 % proof strength measured on the test piece initially pre-strained at 2 % and then heat treated

t_0	Initial gauge thickness before pre-straining
t_1	Gauge thickness after pre-straining
W_0	Initial KS-1B specimen gauge width before pre-straining
W_1	KS-1B specimen gauge width after pre-straining
w_0	Tensile bar gauge width before being pre-strained and excised
w_1	Tensile bar gauge width after being pre-strained and excised

1.4 Referenced Documents

- ASTM A653/653M: Standard Specification for Steel Sheet, Zinc-Coated (Galvanized) or Zinc-Iron Alloy-Coated (Galvannealed) by the Hot-Dip Process
- DS/EN 10325: Steel - Determination of yield strength increase by the effect of heat treatment [Bake-Hardening-Index]

2.0 Test Plan

2.1 Testing Preparation

2.1.1 Sample Nomenclature

Each coupon should be named as follows:

Lot#-Thickness_Grade/Tensile Strength-Coating_BH_Pre-Strain Amount – Repeat #

- Thickness in mm
- Pre-Strain = 2%, 5%, 8% or 10%

Example: The third repeat for 2% pre-strain coupon for Lot#19: 1.00x CR825Y1180T-DP-UNCOATED-U would be labeled as follows:

Lot19-1.00_DP1180-UNC_BH2-3

2.1.2 Preparing Samples

Excise KS-1B coupons (see Appendix A, Figure 3) from the steel sheet with the long axis of the coupon oriented parallel to the rolling direction of the steel sheet.

Each KS-1B coupon should be labeled as described in Section 2.1.1 with the lot number, thickness, and coating. *Example: Lot19-1.00_DP1180-UNC.*

2.2 Test Procedure

2.2.1 Step 1: Coupon measurement

- Measure the initial thickness (t_0) and width (W_0) for each KS-1B coupon and record the values in Table 2.

2.2.2 Step 2: Pre-Strain

- Pre-strain testing using KS-1B specimens to 2%, 5% 8% and/or 10% (±0.05%) at a strain rate of 0.001/s.
- Label each coupon per Section 2.1.1. *Example: Lot19-1.00_DP1180-UNC-BHx-y, where x is the pre-strain amount and y is the repeat number.*
- Measure the post-strain thickness (t_1) and width (W_1) of the KS-1B coupon and record the values in Table 2.
- Save the force / displacement and extensometer data to the spreadsheet as instructed in Section 2.3. The respective spreadsheet tab should be labeled with PFD (Pre-strain Force/Displacement) followed by the pre-strain amount and repeat number. Example: *PFD-BH2-1*.

2.2.3 Step 3: Excise Tensile Bar

- Excise a standard tensile coupon from the KS-1B coupon (Appendix A, Figure 4). Label the coupon per Section 2.1.1. *Example: Lot19-1.00_DP1180-UNC-BHx-y, where x is the pre-strain amount and y is the repeat number.*
- Measure the tensile coupon gauge thickness (t_1) and gauge width (w_1). Record the values in Table 2.

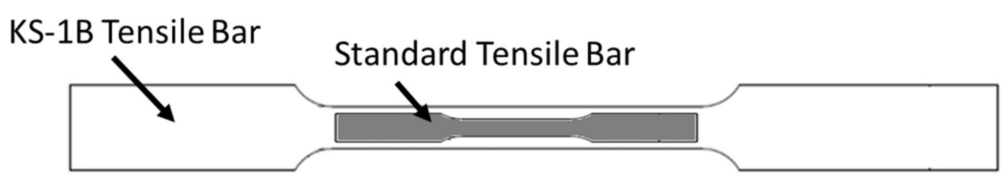

Figure 1: The standard tensile bar excised from the KS-1B Tensile coupon will be uniformly pre-strained

2.2.4 Step 4: Bake Harden

- It is recommended that a thermocouple be attached to the coupon within the gauge length to ensure proper baking. If more than one coupon is to be baked, then first ensure uniformity of the heating chamber and arrange coupons so that there is no overlap.
- Bake ASTM coupons at 170 °C (± 2 °C) for 20 min.
- Remove the coupon(s) from the heating chamber and allow it to air cool to ambient temperature before testing.

2.2.5 Step 5: Tensile Test

- Mount and tensile test the coupon (i.e., ASTM A370).

- Save the force / displacement and extensometer data to the spreadsheet as instructed in Section 2.3. The respective spreadsheet tab should be labeled with TFD (Tensile Force/Displacement) followed by the pre-strain amount and repeat number. Example: *TFD-BH2-1*.

2.2.6 Plot Engineering Stress / Strain

- Plot the pre-strain engineering stress / strain curve using the pre-strain force displacement data and KS-1B coupon dimensions. The gauge area is calculated from the initial thickness and width measurements ($\mathbf{A_{P0} = t_0 \times W_0}$).
  - Record the plot in a spreadsheet tab, which should be labeled with PESS (Pre-strain Engineering Stress/Strain) followed by the pre-strain amount and repeat number. Example: *PESS-BH2-1*.
  - Record the KS-1B gauge area ($\mathbf{a_{P0}}$) in the spreadsheet (Table 2).
  - Record 0.2% offset yield stress ($\mathbf{R}_p$) in the spreadsheet (Table 2).
- Plot the engineering stress / strain curve of the standard tensile coupon using the force displacement data and coupon dimensions t_1 and w_1. The gauge area is used is the effective gauge area of the tensile bar before pre-straining ($\mathbf{a_{T0}} = \mathbf{t_0} \times \mathbf{w_0}$). Since this is not measured before pre-straining it must be back-calculated from the dimensions of the excised tensile bar adjusted for the pre-strain amount. As shown in Equation 1 and illustrated in Figure 2, the ratio of the pre-strained KS-1B gauge width ($\mathbf{W_1}$) to the initial KS-1B gauge width ($\mathbf{W_0}$) will be the same as that of the pre-strained tensile bar ($\mathbf{w_1}$) to the initial standard tensile bar width ($\mathbf{w_0}$). Therefore, $\mathbf{w_0}$ can be calculated and used in Equation 2 to determine the initial standard tensile bar area ($\mathbf{a_{T0}}$).

$$\frac{W_1}{W_0} = \frac{w_1}{w_0} \rightarrow w_0 = w_1 \times \frac{W_0}{W_1} \qquad \textbf{Equation 1}$$

$$\mathbf{a_{T0}} = \mathbf{t_0} \mathrm{x}\, \mathbf{w_0} = \left(\mathbf{w_1 x} \frac{W_0}{W_1}\right) \mathbf{x\, t_0} \qquad \textbf{Equation 2}$$

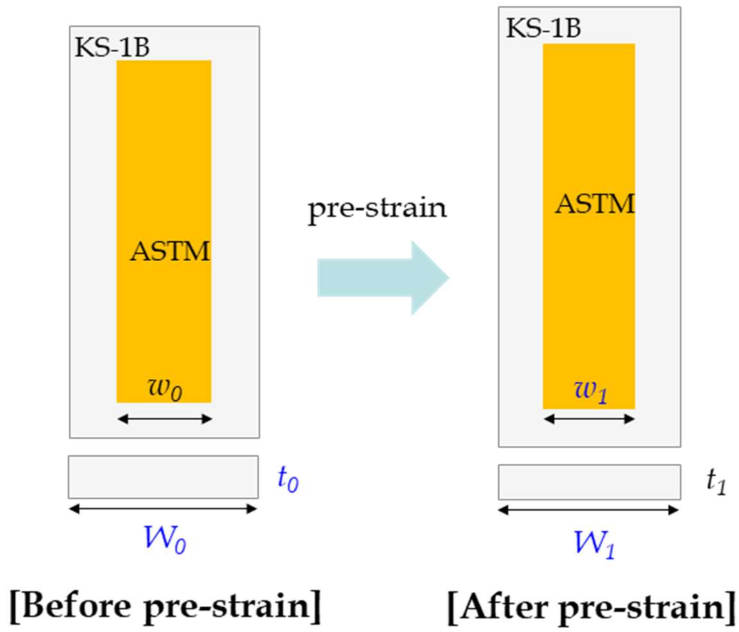

Figure 2: To maintain consistency with the ASTM and EN/DS procedure, the gauge area of the excised tensile coupon is the original area of the coupon before pre-strain.

- Record the plot in a spreadsheet tab, which should be labeled with TESS (Tensile Engineering Stress/Strain) followed by the pre-strain amount and repeat number. Example: *TESS-BH2-1*.
- Record the standard tensile bar initial area ($\mathbf{a_{T0}}$) in the spreadsheet (Table 2).
- Record either the 0.2% offset for the yield stress ($\mathbf{R_{p0.2}}$) or lower limit yield stress ($\mathbf{R_{el}}$), depending on whether yield softening occurs, in the spreadsheet (Table 2).

- Calculate the bake hardening index (BHI) using Equation 3 and record in the spreadsheet (Table 2)

$$\mathbf{BHI} = (\mathbf{R_{p0.2}})\text{or } (\mathbf{R_{el}}) - (\mathbf{R}_{\boldsymbol{p}}) \qquad \text{Equation 3}$$

2.3 Deliverables

Table 1 lists the deliverables and suggested format. To avoid a proliferation of files, a master spreadsheet with tabs is preferred to organize the raw, calculated, and plotted data.

- The spreadsheet file name should reflect the full coupon identification, e.g., *Lot19-1.00_DP1180-UNC_BH.xlsx*

- Each tab label should include the test and coupon information as described in the respective sections above. For example, the following tabs would be created for the five repeats of coupons pre-strained to 2%.
    - *PFD-BH-1, PFD-BH-2, PFD-BH-3, PFD-BH-4, PFD-BH-5*
    - *TFD-BH-1, TFD-BH-2, TFD-BH-3, TFD-BH-4, TFD-BH-5*
    - *PESS-BH-1, PESS-BH-2, PESS-BH-3, PESS-BH-4, PESS-BH-5*
    - *TESS-BH-1, TESS-BH-2, TESS-BH-3, TESS-BH-4, TESS-BH-5*
- The first tab of the file should include a summary table with the coupon dimensional data, the measured yield strengths, and BHI. Table 2 provides the suggested format for the summary table.

Table 1: Test Deliverables

Deliverables	Coupon	Format
Coupon gauge dimensions	KS-1B (pre-test)	Spreadsheet (See Table 2)
	KS-1B (after pre-strain)	
	Standard Tensile Bar	
Force-Displacement Curves	KS-1B (pre-strain)	Spreadsheet Tabs
	Standard Tensile Bar	
Extensometer data	KS-1B (pre-strain)	Spreadsheet Tabs
	Standard Tensile Bar	
Engineering Stress – Strain Curves	KS-1B (pre-strain)	Spreadsheet Tabs
	Standard Tensile Bar	
Bake Hardening Index		Spreadsheet (See Table 2)

Table 2: BHI Table

Material: Lot19-1.00_DP1180-UNC														
KS-1B Coupon								Standard Tensile Coupon						BHI
Coupon Designation	Pre-strain Amount	Original Thickness (t_0)	Original Width (W_0)	Guage Area ($A_{P0} = W_0 * t_0$)	Pre-Strain Thickness (t_1)	Pre-Strain Width (W_1)	2% offset YS (R_p)	Width (w_0) (calculated)	Guage Area ($A_{T0} = w_0 * t_0$)	Width (w_1)	Thicknes (t_1)	2% offset YS ($R_{p0.2}$)	Lower Limit YS (R_{el})	
Lot19-1.00_DP1180-UNC_BH2-1														
Lot19-1.00_DP1180-UNC_BH2-2														
Lot19-1.00_DP1180-UNC_BH2-3														

3.0 Appendix A: KS-1B Coupon

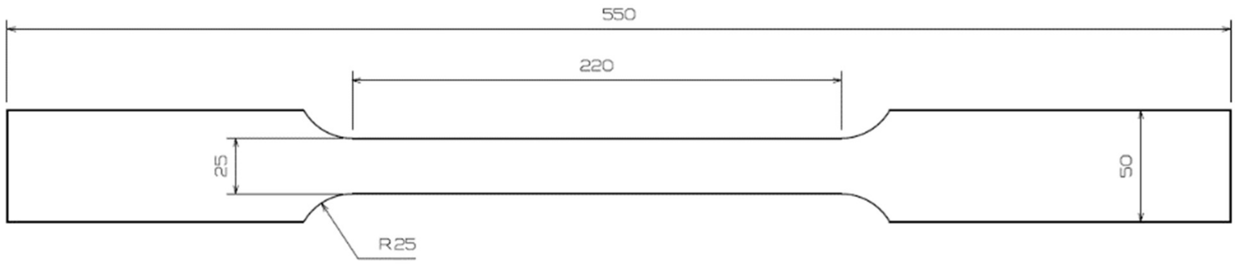

Figure 3: KS-1B Coupon Geometry

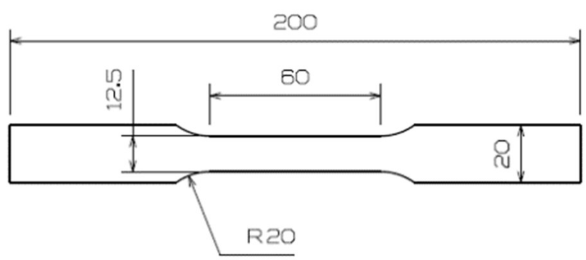

Figure 4: Tensile Coupon Geometry