Deformation & Edge Stretchability Of Multiphase Steels After Shear Cutting

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GREAT DESIGNS IN STEEL™

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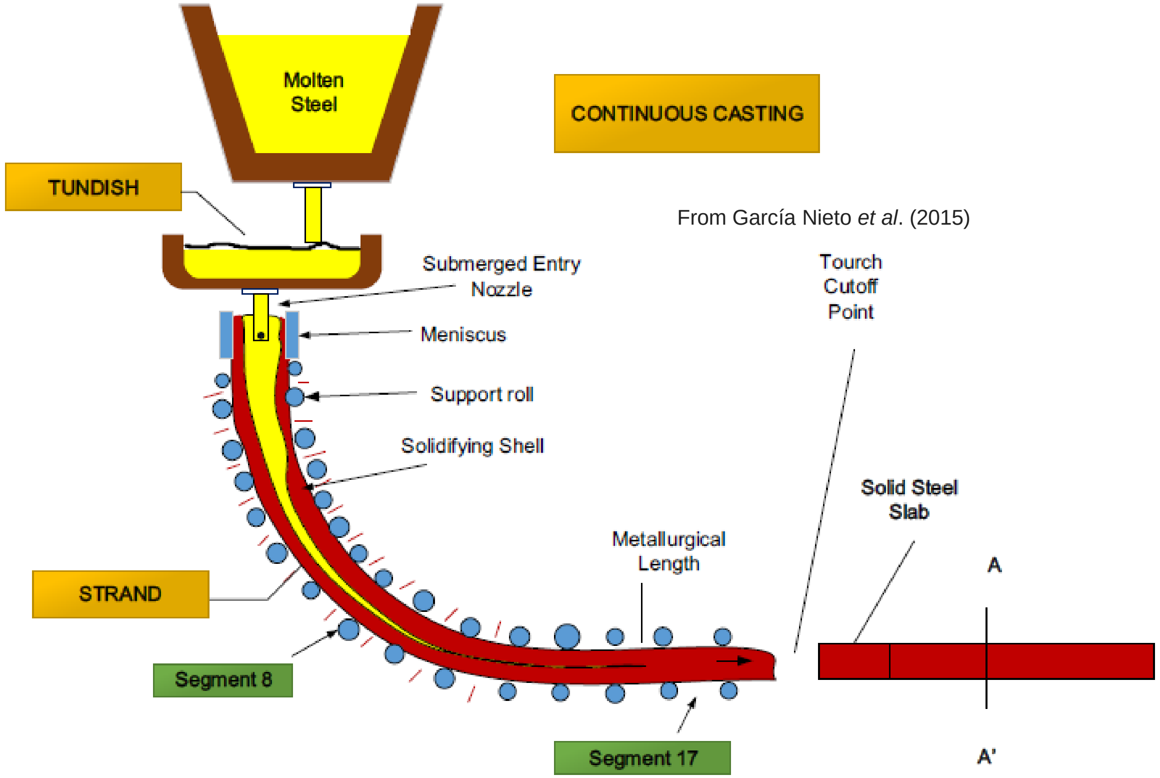
Outline

- Introduction to Cut Edge Fissures
- Objectives
- Materials of Interest
- Hole Punching Parameters
- Sheared Edge Hardness Distribution
- Conical Hole Expansion Test
- In-Plane Bending Test
- Hole Tension Test at 12% Clearance
- Summary & Future Work

Introduction: Centerline Segregation in Steels

- **Presence and concentration of Ti or Mn-inclusions can occur at mid-thickness in multiphase steels.**
- Phenomenon occurs during continuous casting & hot rolling of molten steel containing such alloying elements.
- Higher solidification rate at the surface → alloying elements accumulate near slab mid-thickness.



From García Nieto *et al*. (2015)

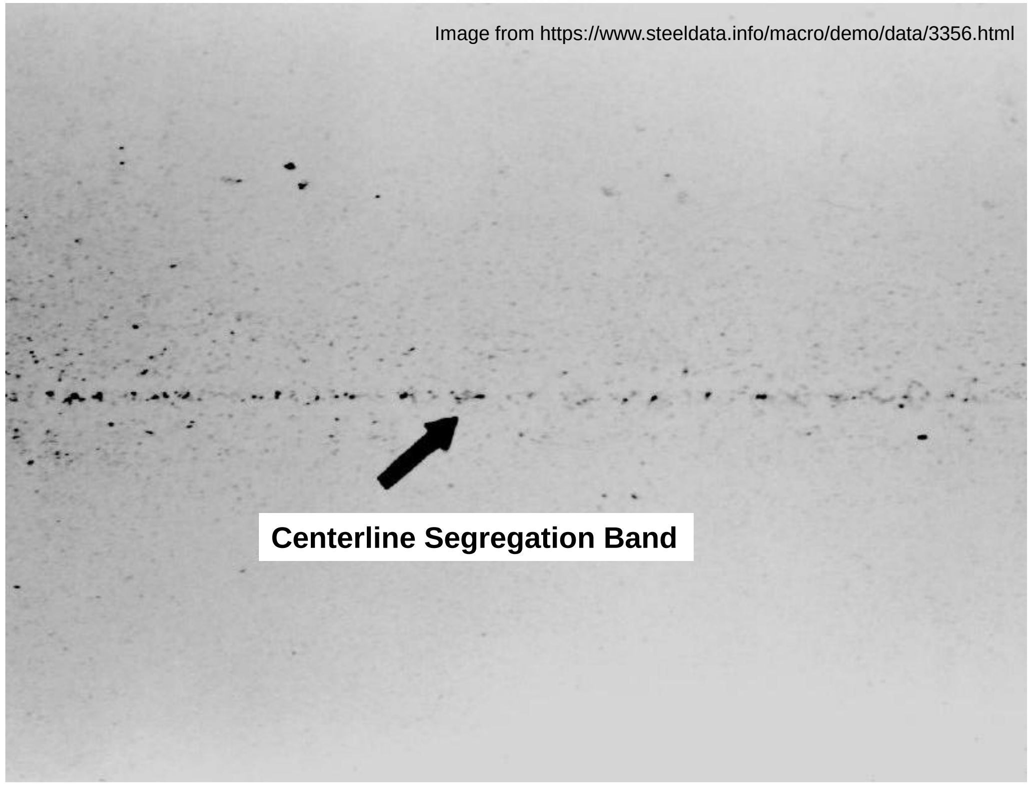
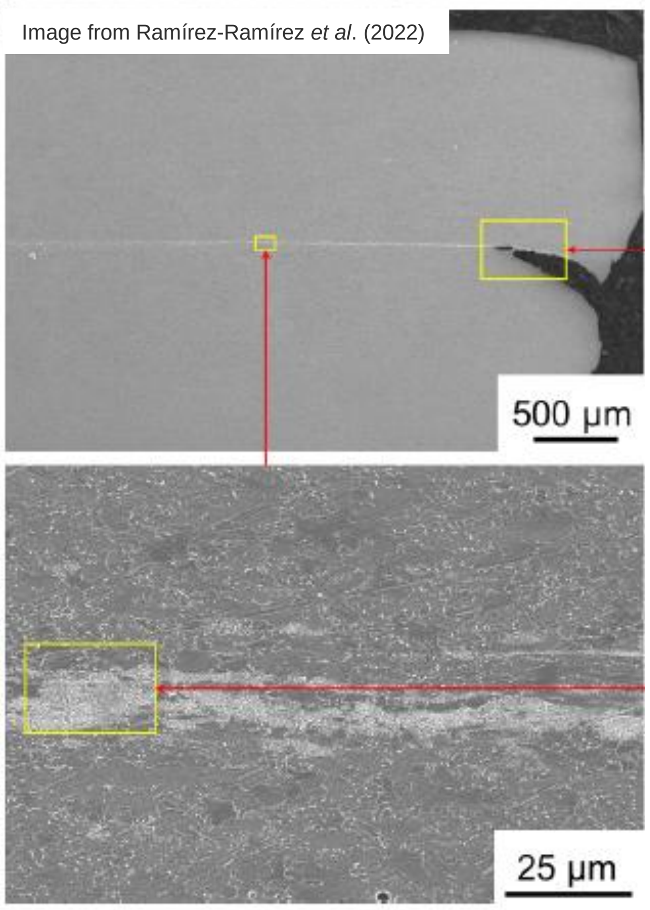


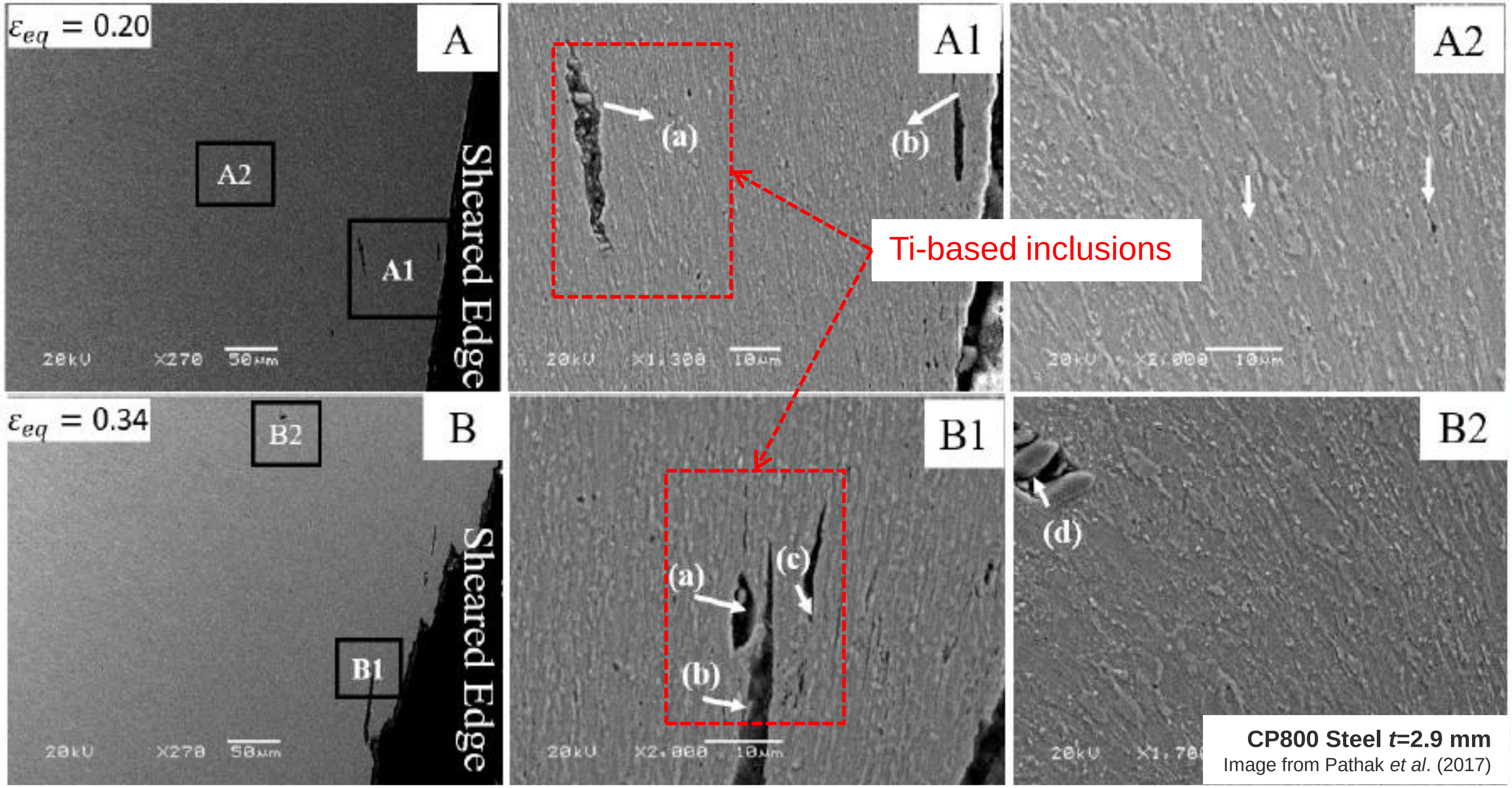
Image from https://www.steeldata.info/macro/demo/data/3356.html

García Nieto, P.J., Gonzalez Suarez, V.M., Álvarez Antón, J.C., Mayo Bayón, R., Sirgo Blanco, J.Á. and Díaz Fernández, A.M., 2015. A new predictive model of centerline segregation in continuous cast steel slabs by using multivariate adaptive regression splines approach. *Materials*, *8*(6), pp.3562-3583.

Susceptibility to Cut Edge Fissures

- **Presence of centerline segregation can trigger fissures during the shear cutting process.**
- Ti-based inclusions can also act as source of cracks during stretching of the sheared edge...



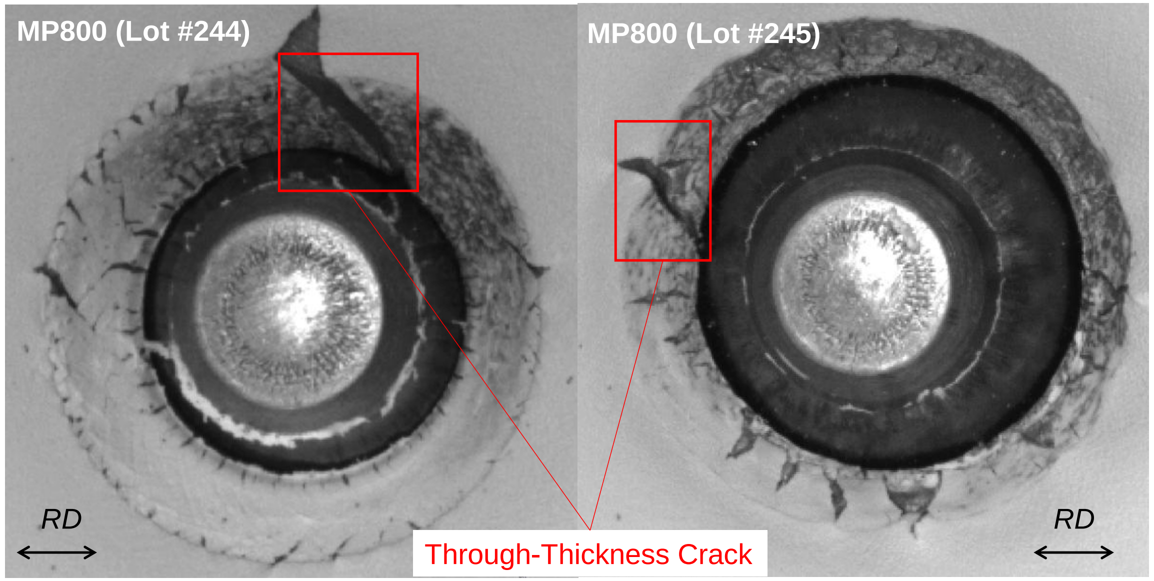


Ramírez-Ramírez, J.H., Pérez-González, F.A., Zapata-Hernández, O.J., Gutiérrez-Platas, J.L., Hernández, L.E., Quiñones, M.A., Garza-Montes-de-Oca, N.F. and Colás, R., 2022. Failure analysis of an advanced high-strength steel. *Engineering Failure Analysis*, *131*, p.105893.
Pathak, N., Butcher, C., Worswick, M.J., Bellhouse, E. and Gao, J., 2017. Damage evolution in complex-phase and dual-phase steels during edge stretching. *Materials*, *10*(4), p.346.

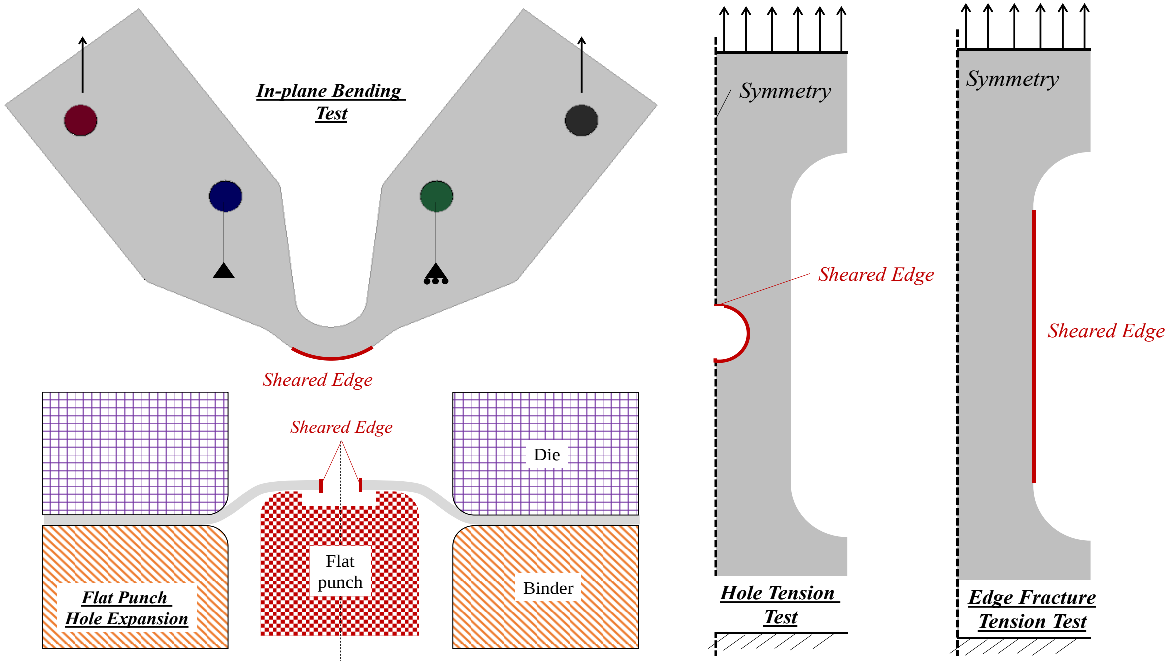
Detection of Cut Edge Fissure Susceptibility

- Centerline segregation detection requires spectroscopy or etching and optical imaging→ time and cost intensive.
- **Can sheared edge stretching behaviour correlate to cut edge fissure susceptibility in steel coils?**
- Conical hole expansion is standardized. Alternate tests deform the centerline and shear affected zone in different modes.

Conical HX (12% CI) –Insight into Cut Edge Fissure Susceptibility?



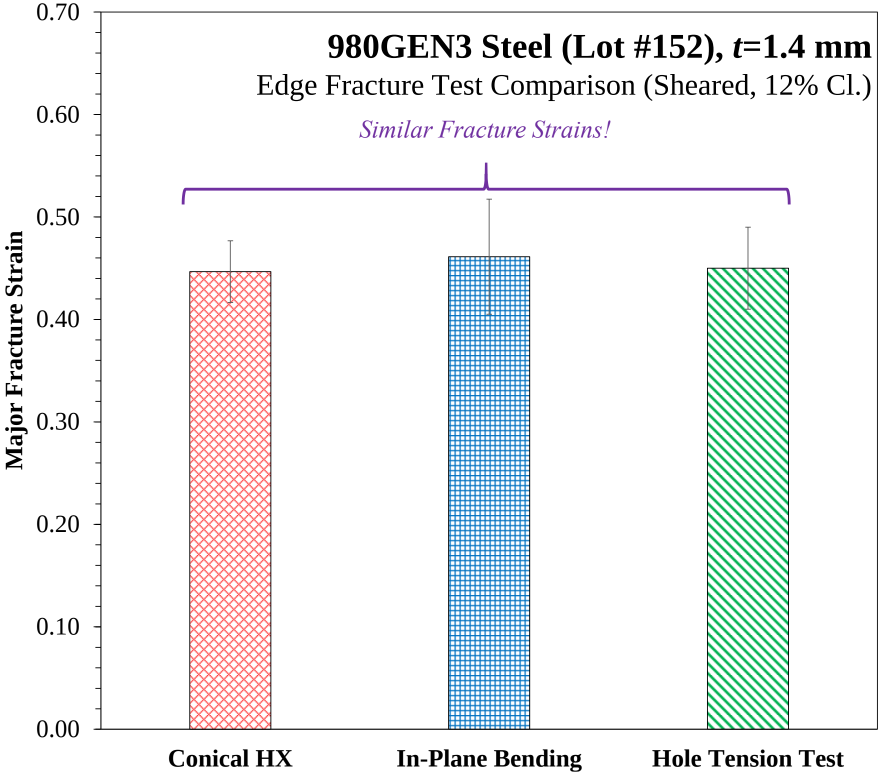
Alternate Edge Fracture Test Techniques



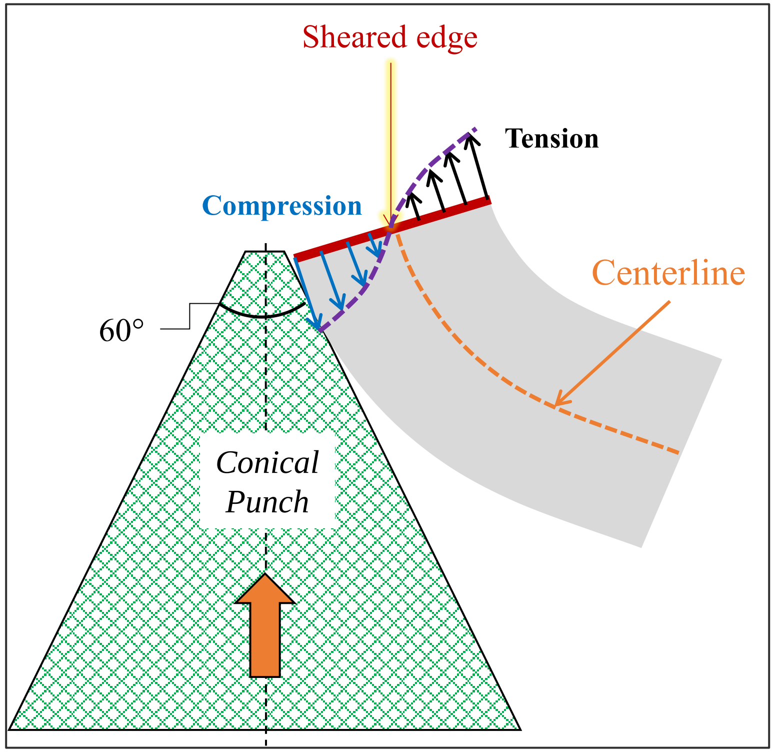
Boundary Condition Effect in Edge Fracture Tests

- Recap: Previous work conducted on 980GEN3 steel revealed minimal edge sensitivity to boundary condition at 12% clearance.
- **However, fracture limits can diverge between the tests for hot-rolled MP800 steels due to centerline effects.**
- Conical HX → *Centerline crack propagation can be delayed due to punch contact.* In-plane Bending→ *centerline in uniaxial tension.*

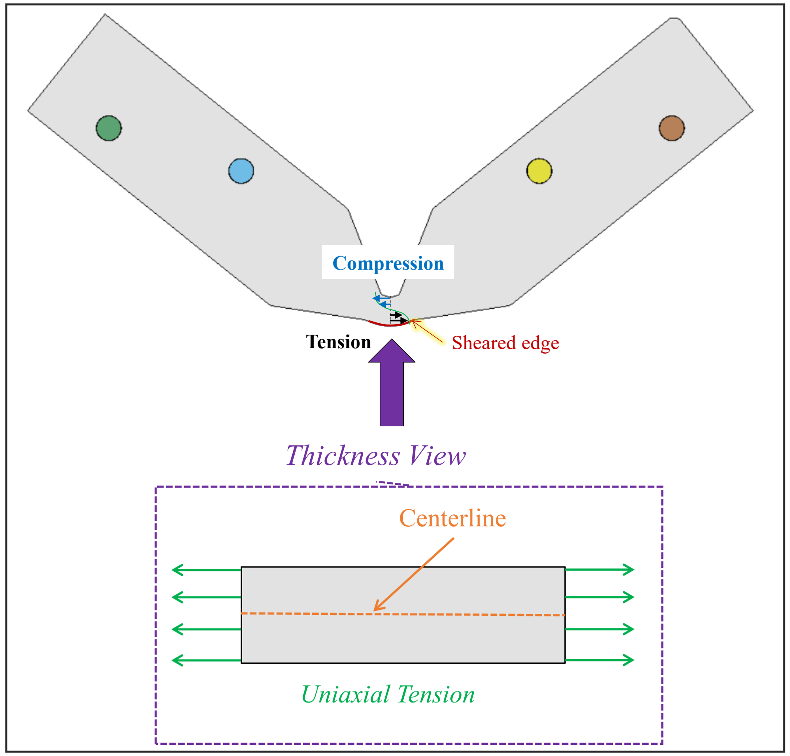
980GEN3 Fracture Strains (12% Cl.)



Conical HX Deformation Mode: Initial Stages



In-Plane Bending Deformation Mode

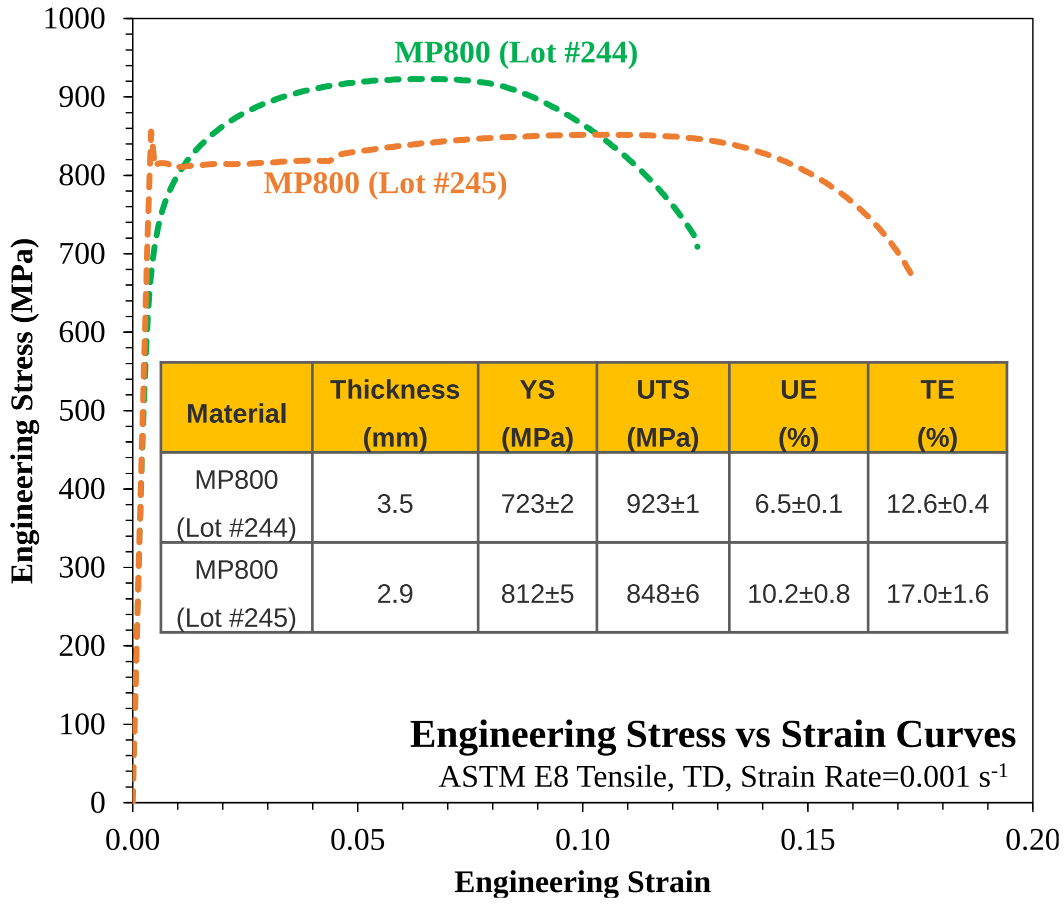


Objectives

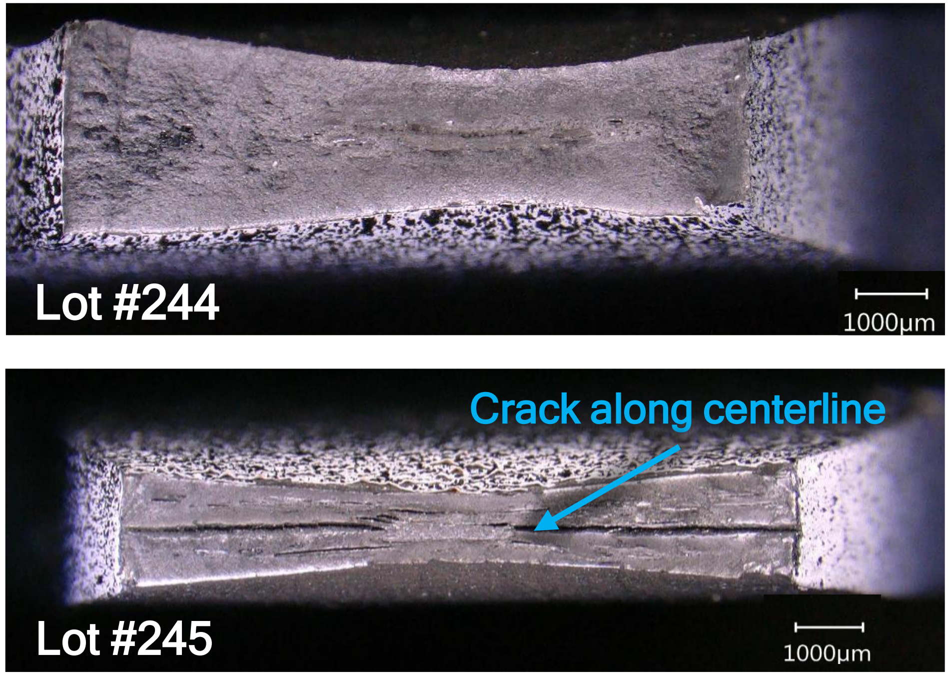
- Determine the effect of clearance on edge stretchability, centerline crack initiation & propagation.
- Assess the effect of edge stretching methods on sheared edge fracture limits of steels with centerline segregation.
- Identify coupon test(s) that are able to trigger centerline effects to identify cut edge fissure susceptibility.
- **Two hot-rolled MP800 steels with different centerline segregation severity are considered for this work.**
- *980GEN3 steel edge fracture characterization results from GDIS 2024 are also revisited for selected cases.*

Materials of Interest

- Two lots of MP800 steels considered. Lot #245 has higher elongation and a lower hardening rate than Lot #244.
- **Higher cut edge fissure susceptibility in Lot #245→ centerline cracks observed in ruptured tensile specimens.**



Material	Thickness (mm)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
MP800 (Lot #244)	3.5	723±2	923±1	6.5±0.1	12.6±0.4
MP800 (Lot #245)	2.9	812±5	848±6	10.2±0.8	17.0±1.6

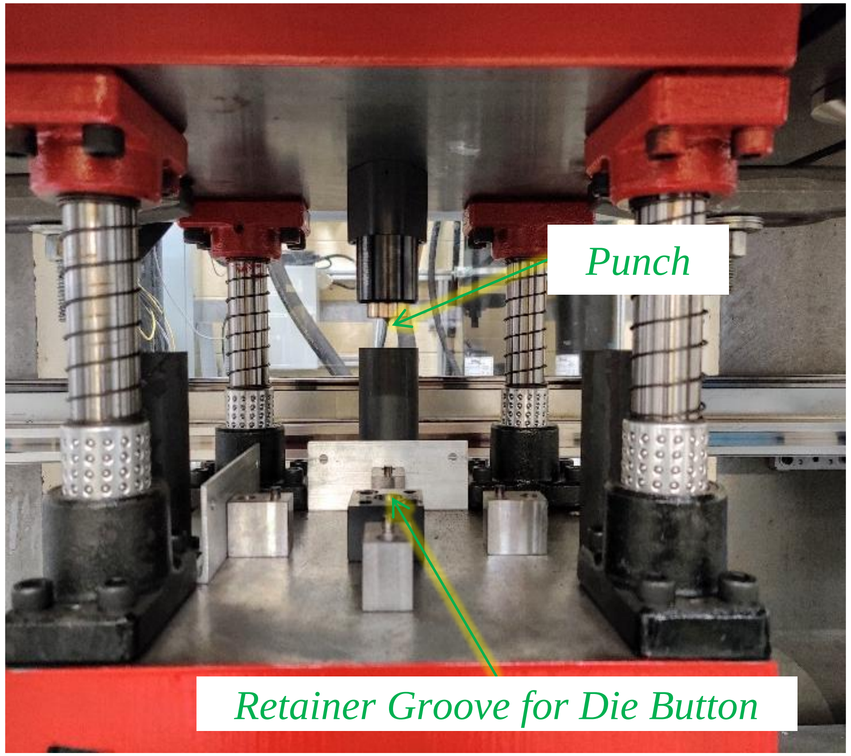


Lot #245 tensile fracture surface can correlate to edge fissure susceptibility during shearing

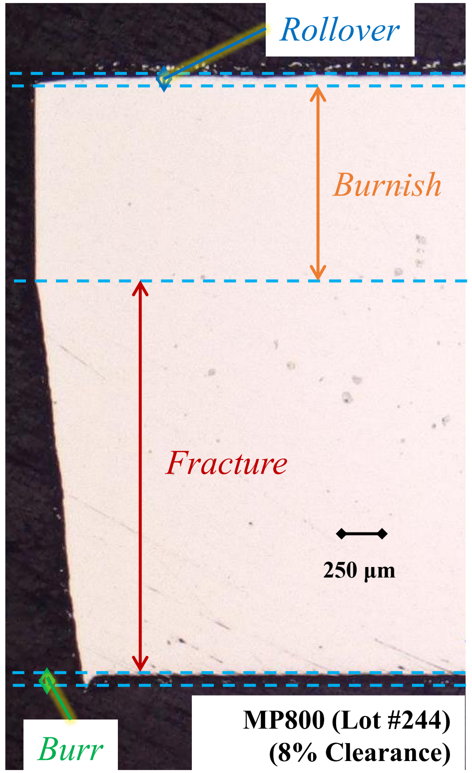
Hole Punching Parameters & Edge Geometry

- **Four clearances considered : 5%, 8%, 12%, and 20%. Hole size of 5 mm (circle or square).**
- Edge profile dominated by burnish & fracture zones. Minimal rollover and burr.

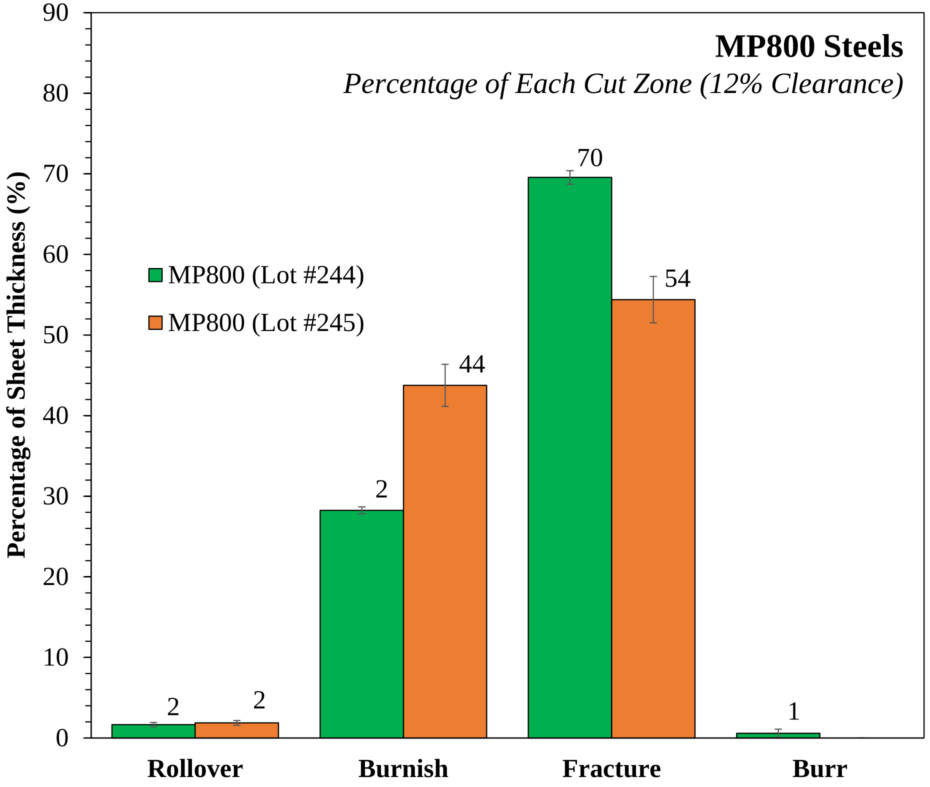
Hole Punching Tool



Sheared Edge Profile



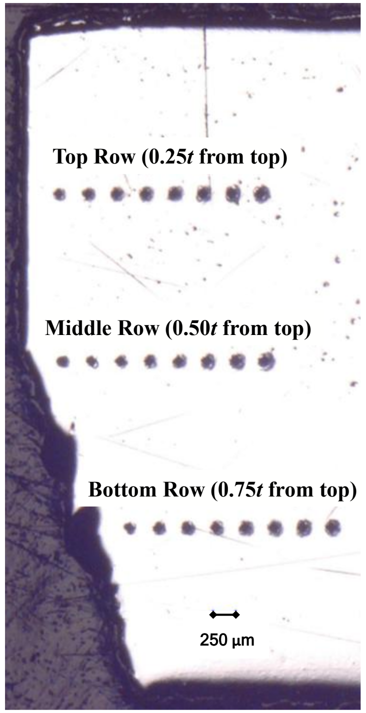
Percentage of Each Cut Zone (12% Clearance)

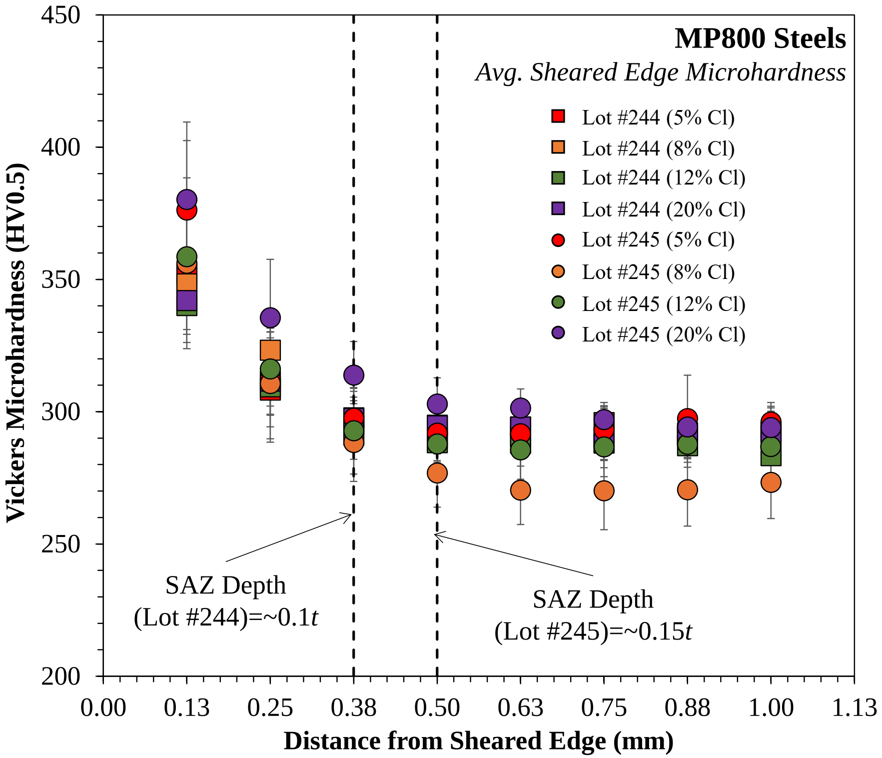


Sheared Edge Hardness Distribution

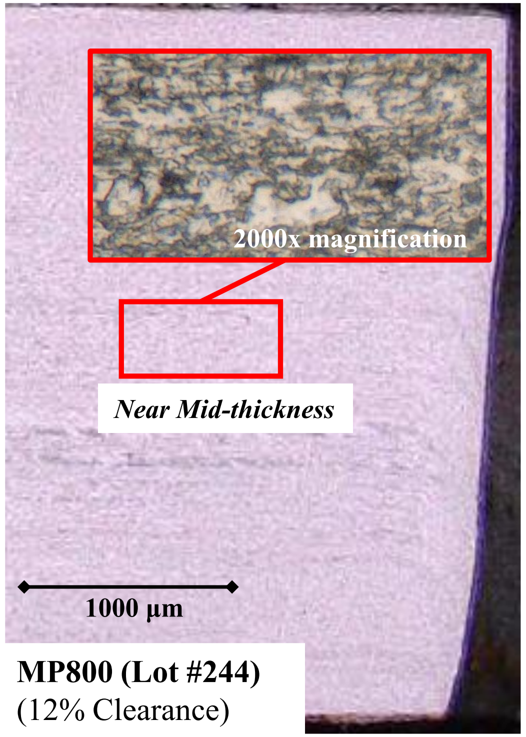
- Average hardness of SAZ statistically similar for the two MP800 steels across all clearances.
- **Presence of Ti-based inclusions near mid-thickness observed for Lot #245 after etching.**

Variation of Avg. Hardness with Distance from Sheared Edge

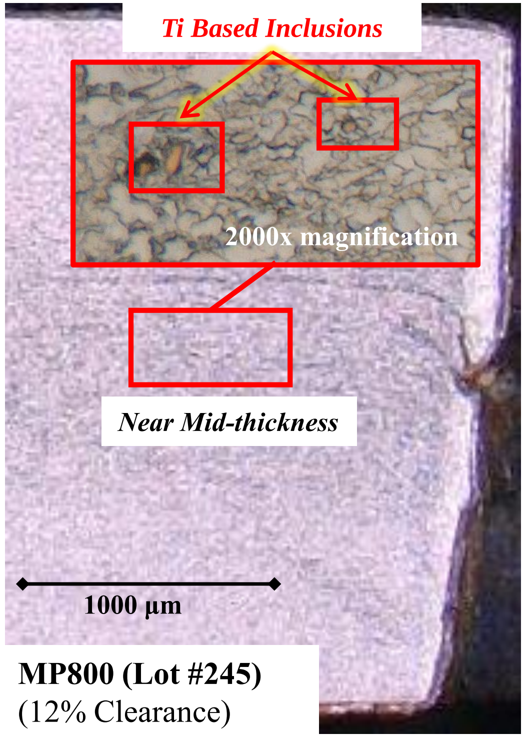




Sheared Edge Views After Etching



MP800 (Lot #244)
(12% Clearance)

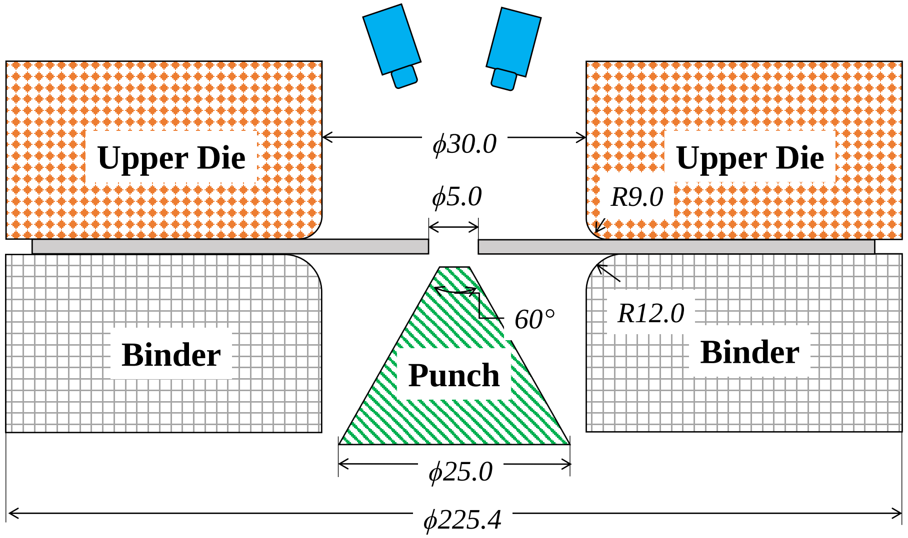


MP800 (Lot #245)
(12% Clearance)

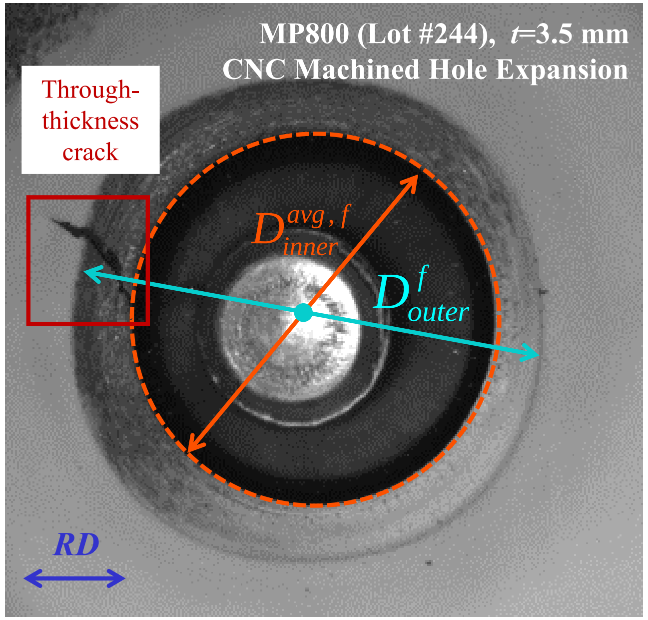
Conical Hole Expansion (HX) Test

- Standardized sheared edge stretching test. Hole diameter of 5.0 mm adopted to reduce chances of necking.
- Test can be monitored continuously using cameras to analyze through-thickness crack image post failure.
- **Major fracture strain can be obtained from outer hole geometry without need for DIC!**

Conical Hole Expansion Setup



Measurements from Conical HX



➔ **Hole expansion ratio:**

$$HER(\%) = \left(\frac{D_{inner}^{avg,f} - D_0}{D_0} \right) \times 100$$

➔ **Major fracture strain:**

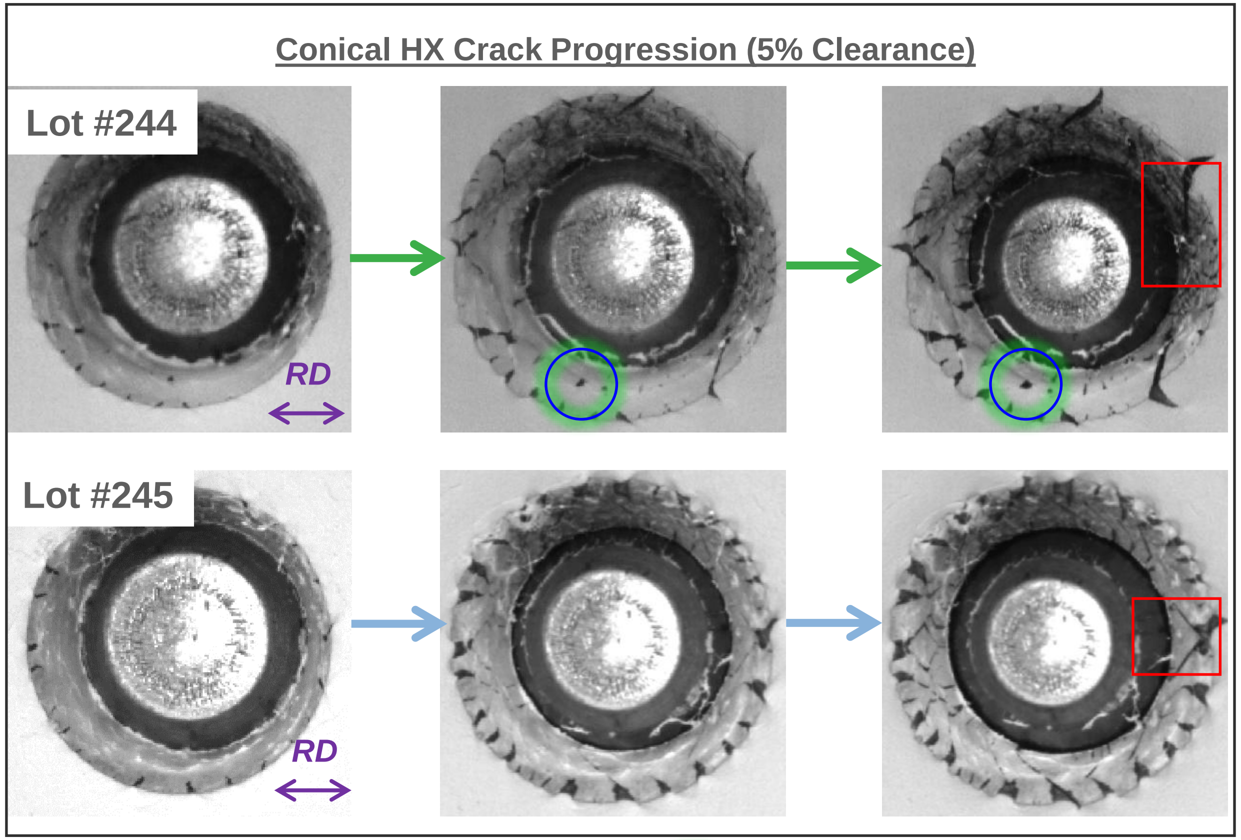
$$\varepsilon_1^{HX} = \ln\left(\frac{D_{outer}^{f}}{D_0} \right)$$

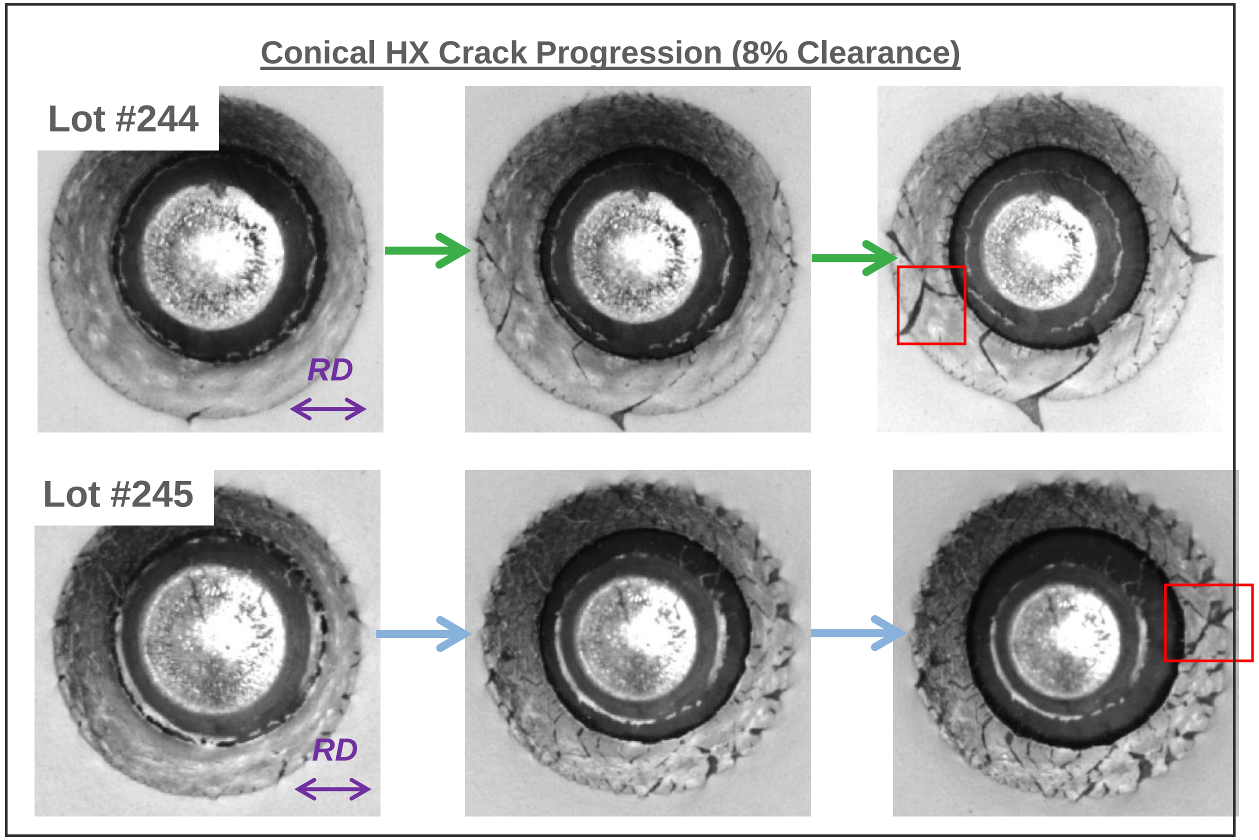
➔ **Initial Diameter:** $D_0 = 5.0\,mm$

Narayanan, A., Abedini, A., Khameneh, F. and Butcher, C., 2023. An experimental methodology to characterize the uniaxial fracture strain of sheet metals using the conical hole expansion test. *Journal of Materials Engineering and Performance*, *32*(10), pp.4456-4482.

Conical HX Deformation (5% and 8% Clearances)

- Few cracks can be observed at mid-thickness for 5% clearance for Lot #244 having lower edge fissure susceptibility.
- Cracks primarily initiated from the edges to then propagate through-thickness at 5% and 8% clearances for Lot #245.



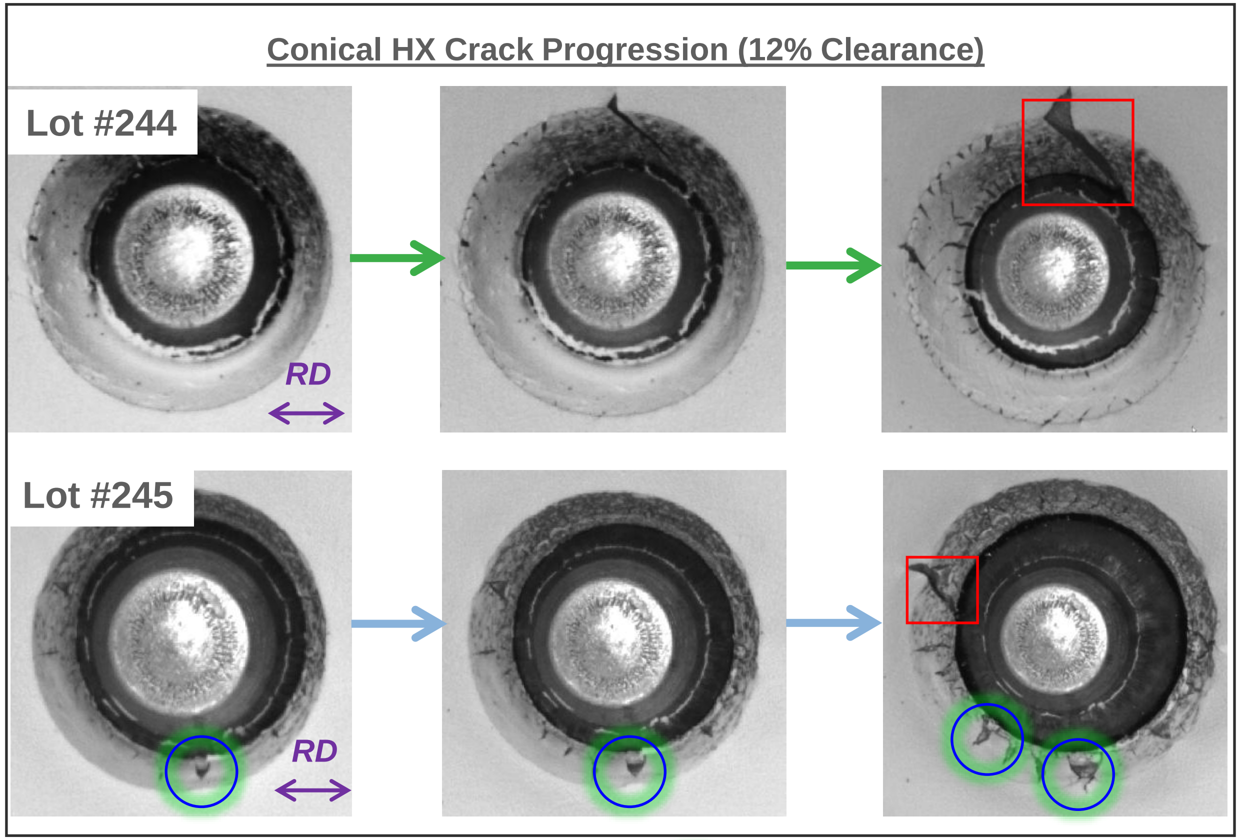


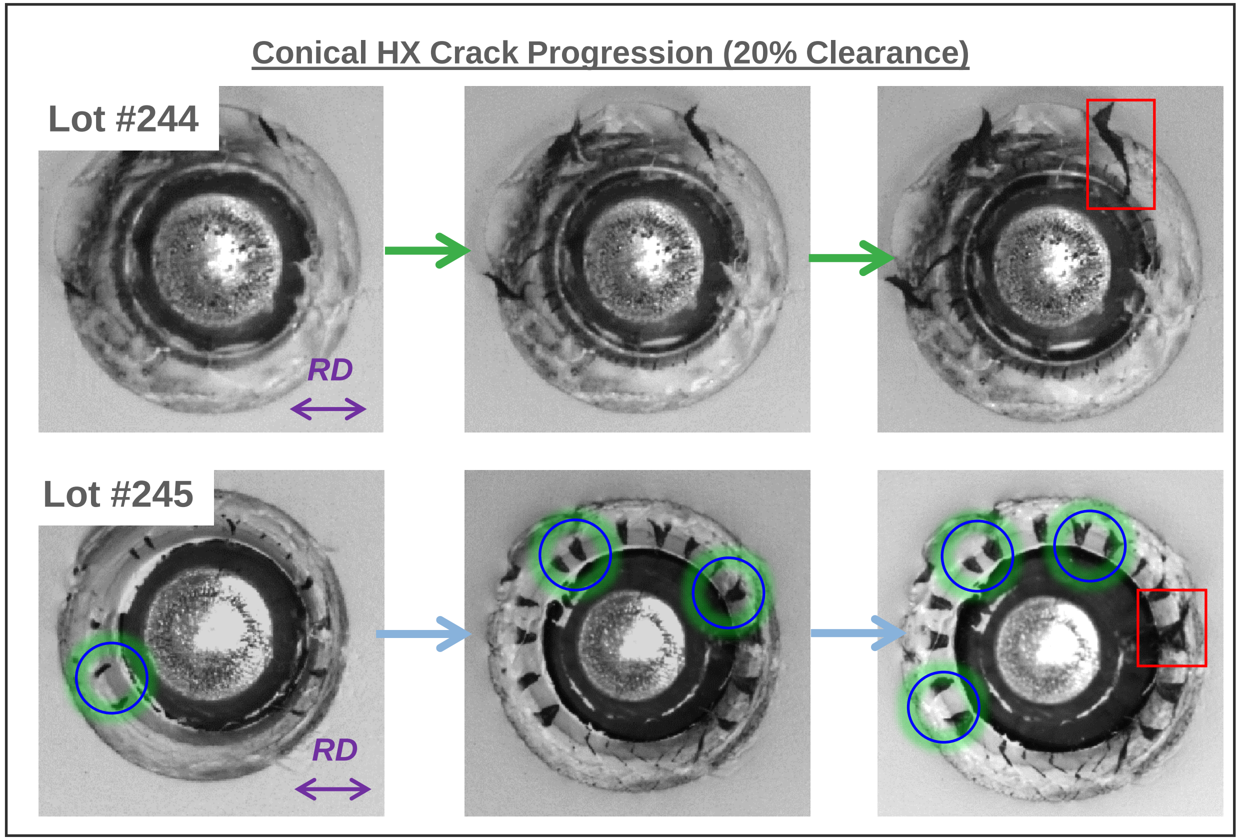
Crack at centerline/mid-thickness

Through-thickness Crack

Conical HX Deformation (12% and 20% Clearances)

- **Several centerline cracks observed in Lot #245 during conical HX of holes punched at 12% and 20% clearances.**
- No mid-thickness cracks observed during conical HX of punched Lot #244 samples except at 5% clearance.



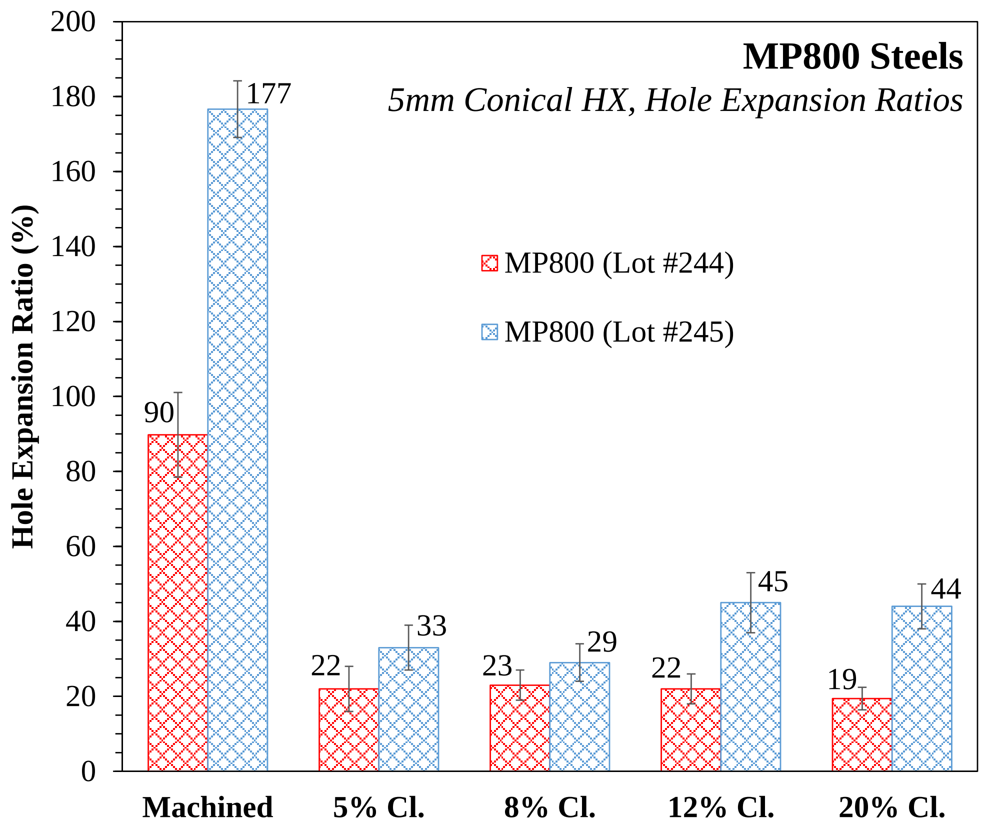


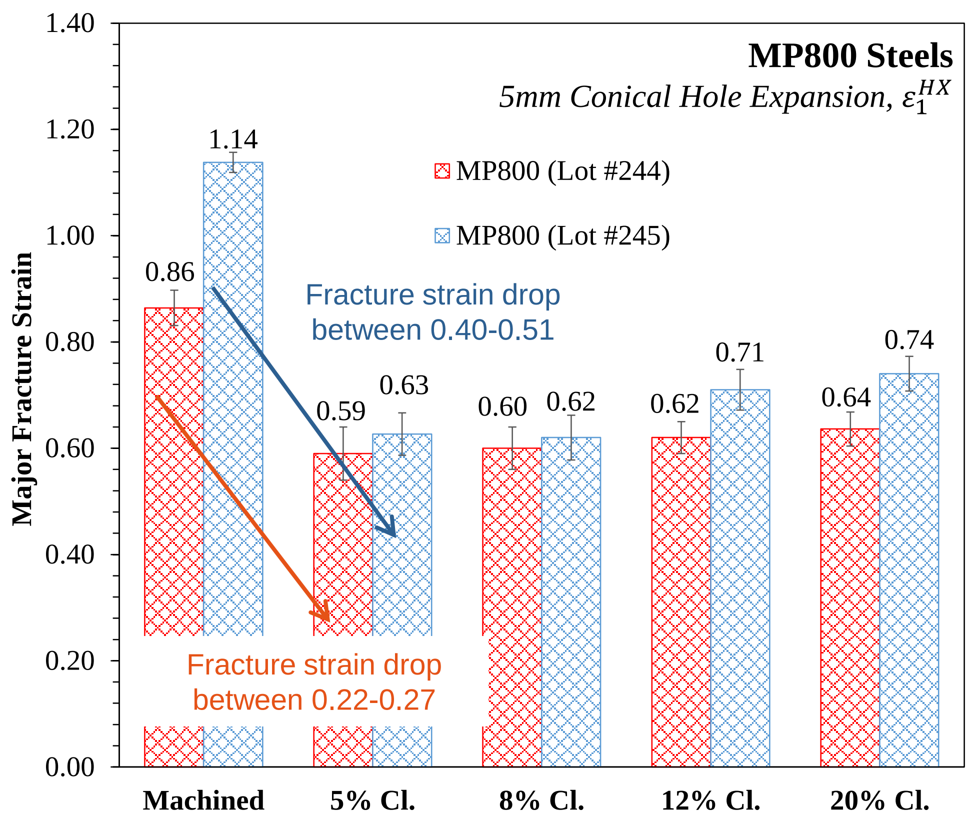
Crack at centerline/mid-thickness

Through-thickness Crack

Conical HX: MP800 Fracture Strains

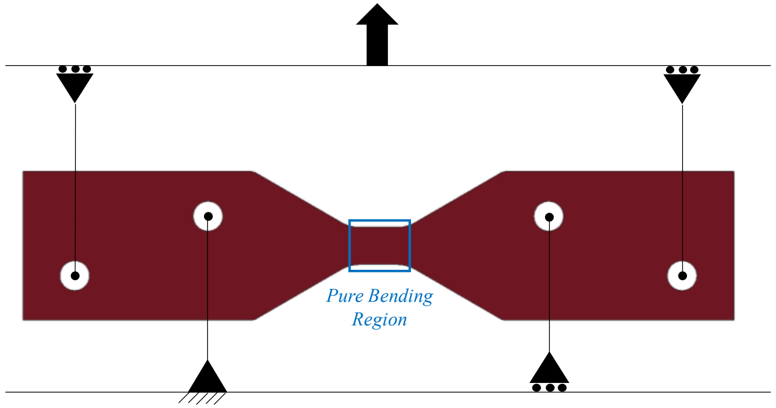
- **Higher delta in HER and fracture strain observed after shearing for Lot #245.**
- Negligible clearance effect for Lot #244. Lot #245 has highest fracture strains for 12% and 20% clearances.

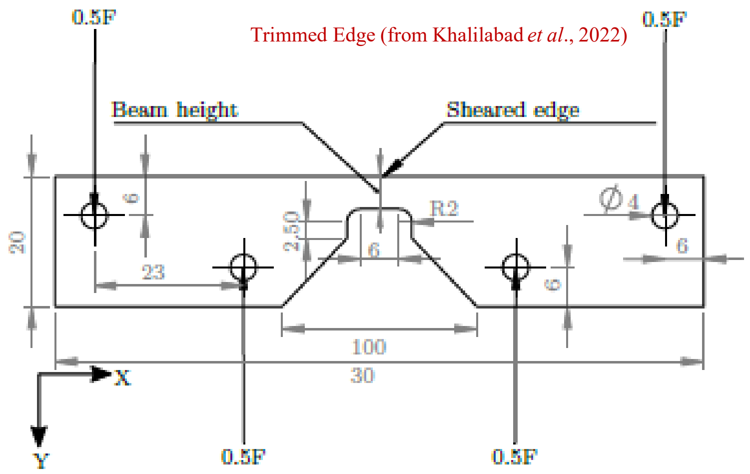


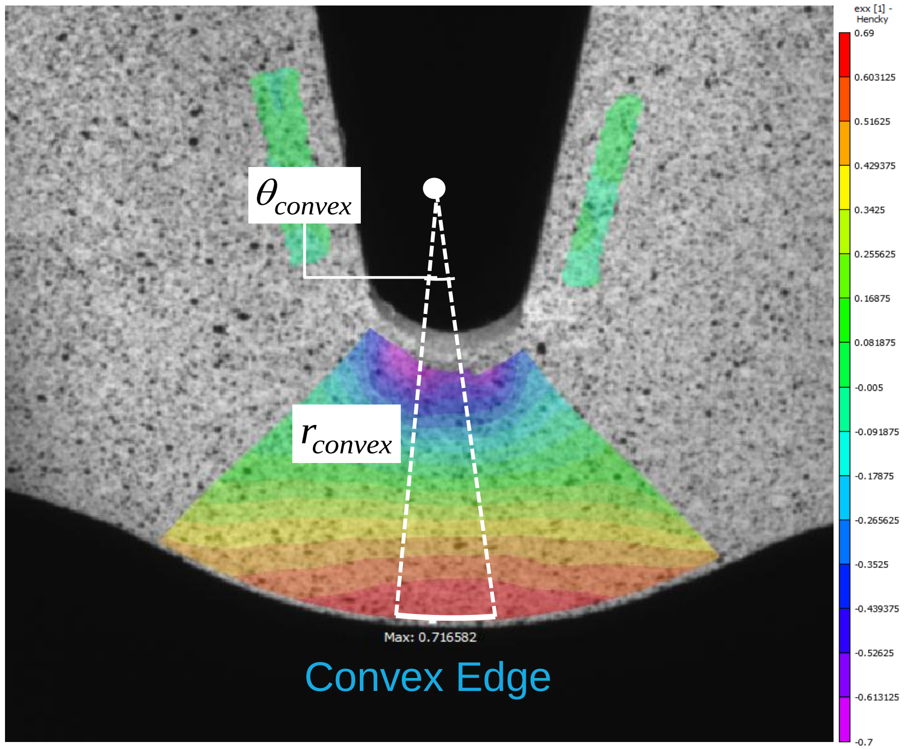


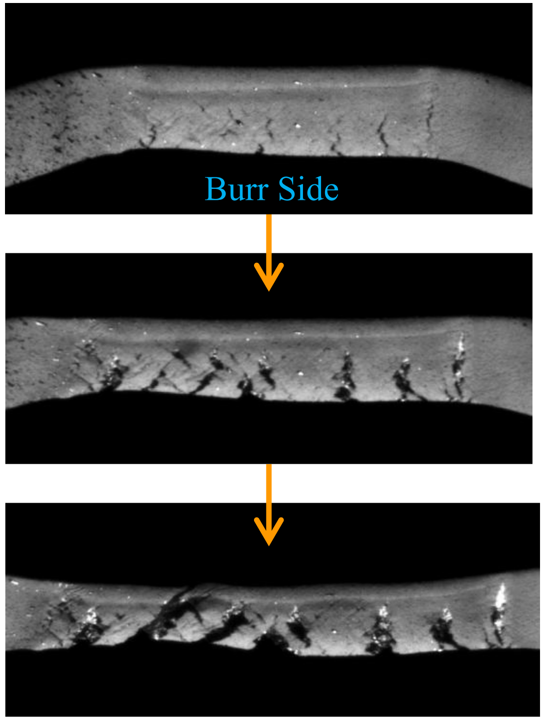
In-Plane Bending (IPB): Overview

- A 4-point bending deformation in the plane of the sheet. Initial design proposed by Naseem *et al*. (2020).
- Fracture strain can be readily measured using DIC or from convex edge geometry (i.e. radius and angle).
- **View of sheet thickness and fracture surface evolution can be tracked using an additional camera.**





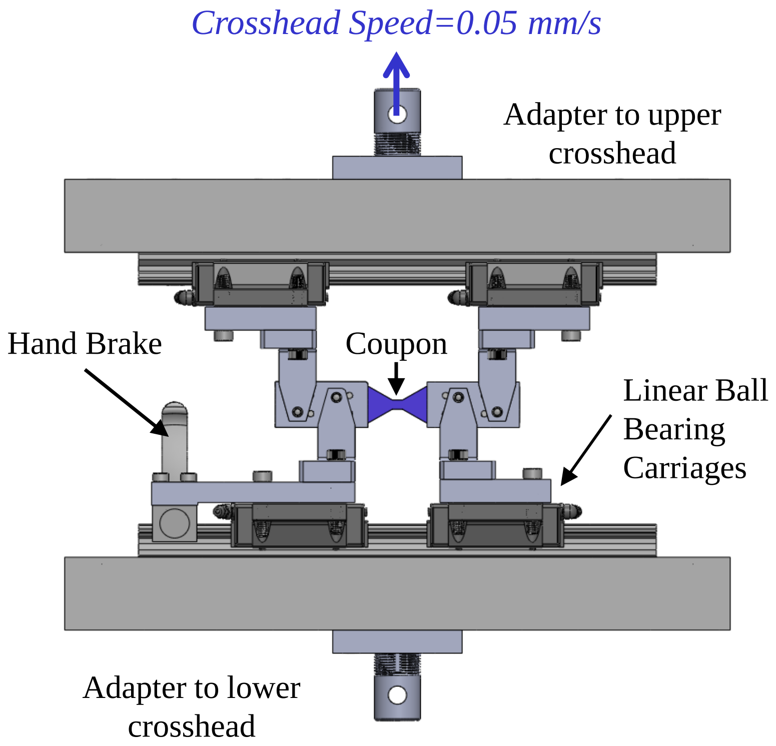


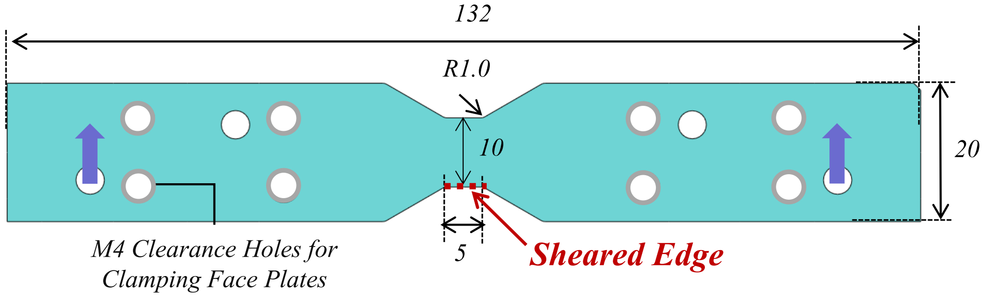


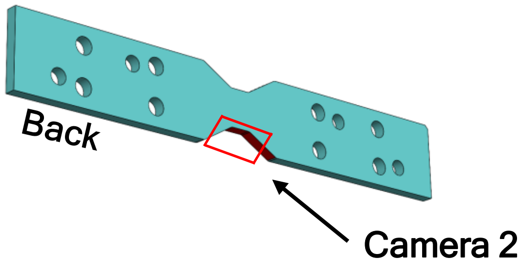
Naseem, S., Perdahcıoğlu, E.S., Geijselaers, H.J.M. and van den Boogaard, A.H., 2020. A new in-plane bending test to determine flow curves for materials with low uniform elongation. *Experimental Mechanics*, *60*, pp.1225-1238.
Masoumi Khalilabad, M., Perdahcioğlu, E.S., Atzema, E.H. and van den Boogaard, A.H., 2022, May. Measurement of edge fracture strain of dual-phase steels by in-plane bending test. In *Materials Science and Engineering Conference Series* (Vol. 1238, No. 1, p. 012039).

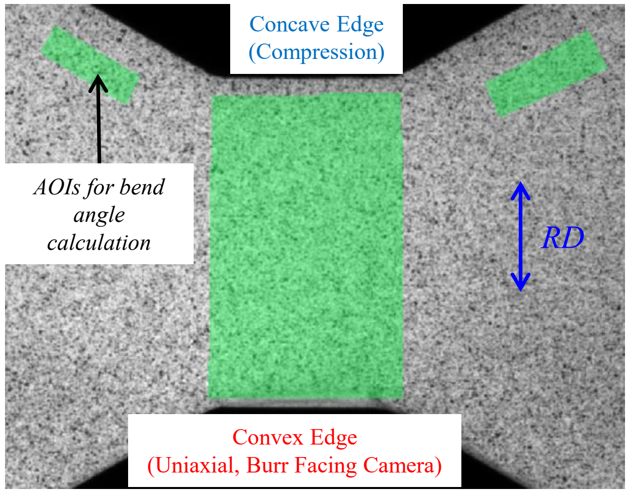
In-Plane Bending: Test Setup

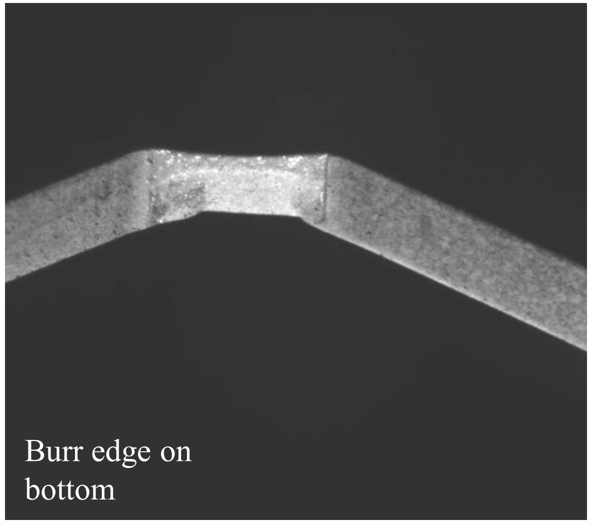
- Fixture installed on a Shimadzu AGS-X tensile frame with 10 kN load capacity. Principal stretching in TD.
- Gauge section dimensions of the specimen chosen to prevent out-of-plane buckling during deformation.
- Sheared edge placed on convex side under tension. A 2nd camera was placed underneath to monitor crack propagation.





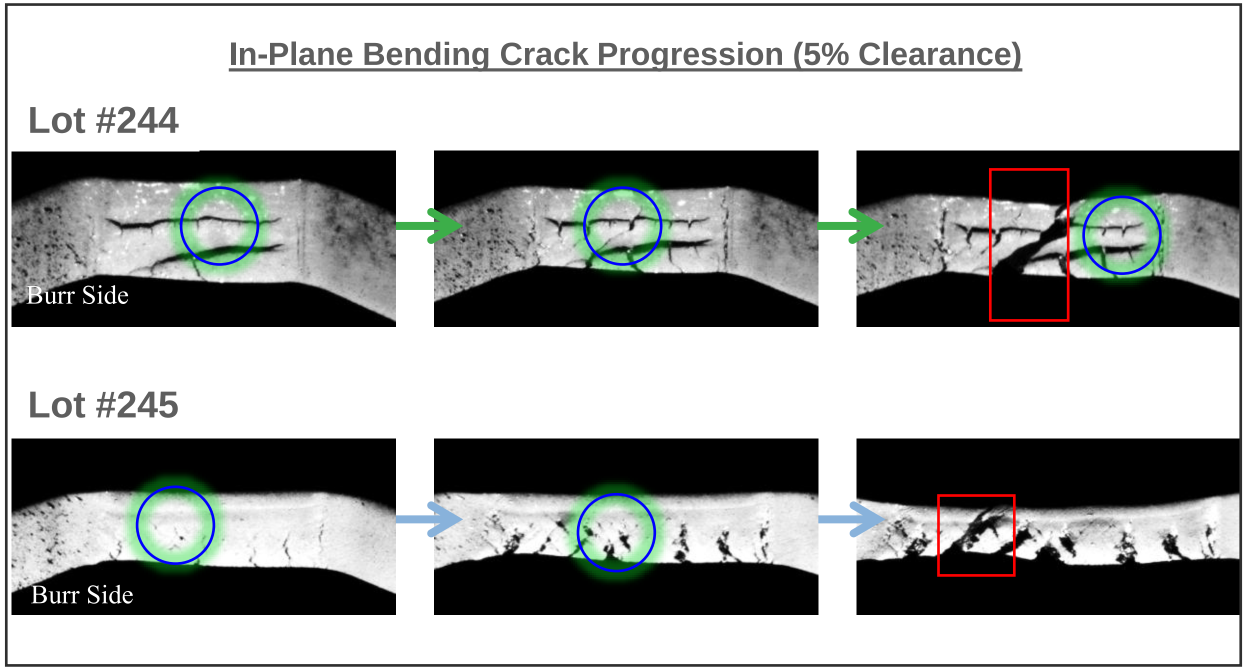


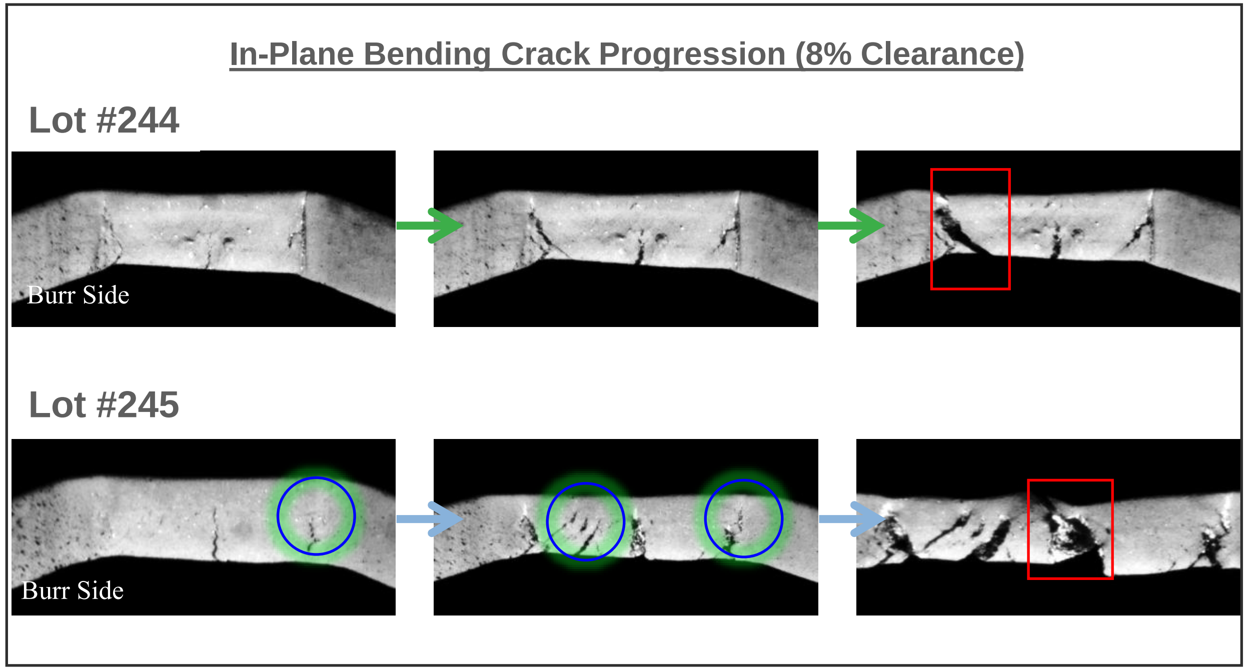




IPB Deformation (5% and 8% Clearances)

- **Centerline crack occurrence in Lot #244 at 5% clearance→ consistent with conical HX observations.**
- Cracks initiate from the burr side for Lot #244 in-plane bend test conducted with 8% clearance.
- Few centerline microcracks observed for Lot #245 as well at both 5% and 8% clearances.



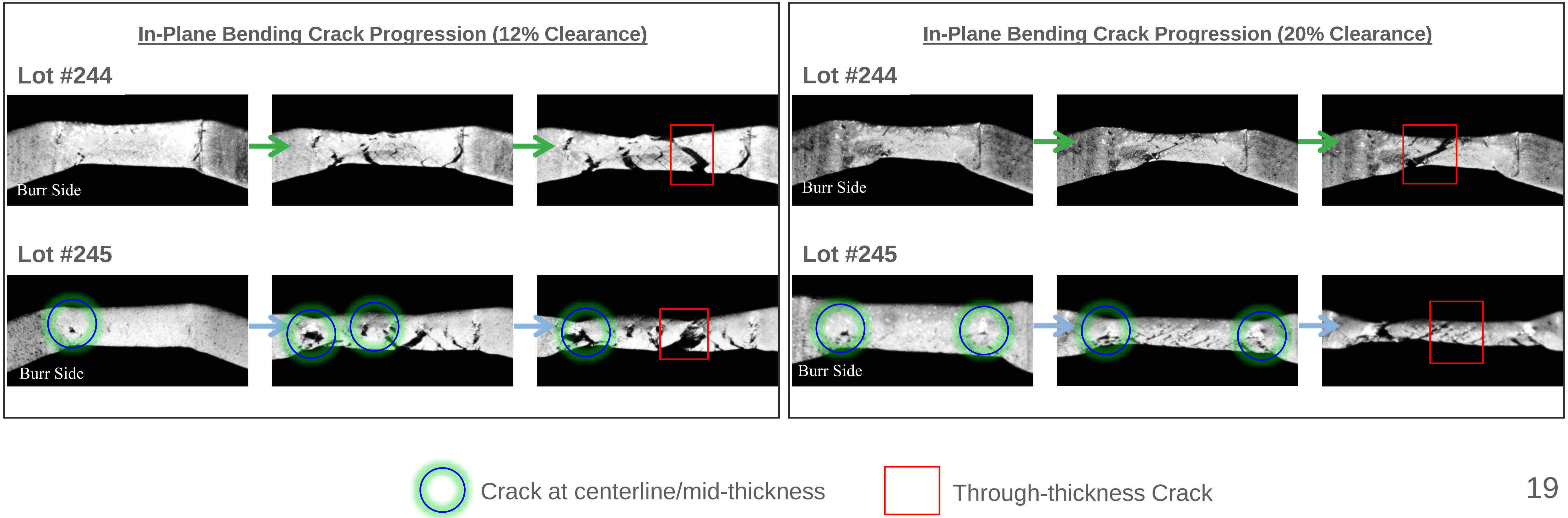


Crack at centerline/mid-thickness

Through-thickness Crack

IPB Deformation (12% and 20% Clearances)

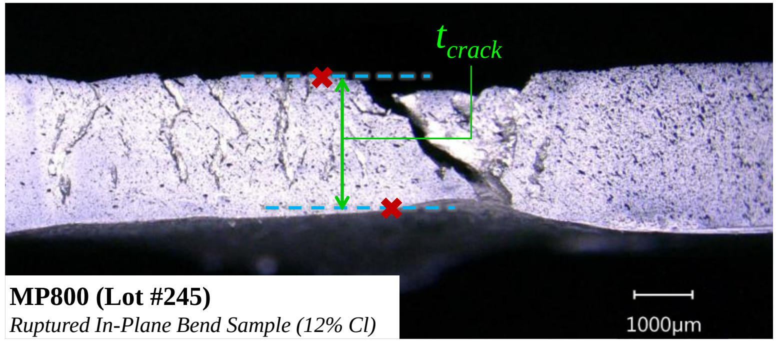
- Cracks initiated on the burr side in Lot #244 bend tests at 12% and 20% cl.
- **Numerous cracks develop at centerline for 12% and 20% clearances for Lot #245.**



In-Plane Bending: MP800 Fracture Strains

- Post-rupture thickness was converted to fracture strain to correspond to similar fracture instant as conical HX.
- Strong boundary condition effect observed for Lot #244 at 5% and 8%. Reduced sensitivity at higher clearances.
- **Marginal influence of applied loading on fracture strains for Lot #245 at all clearances except 8%.**

Fracture Strain from Post-Mortem Thickness



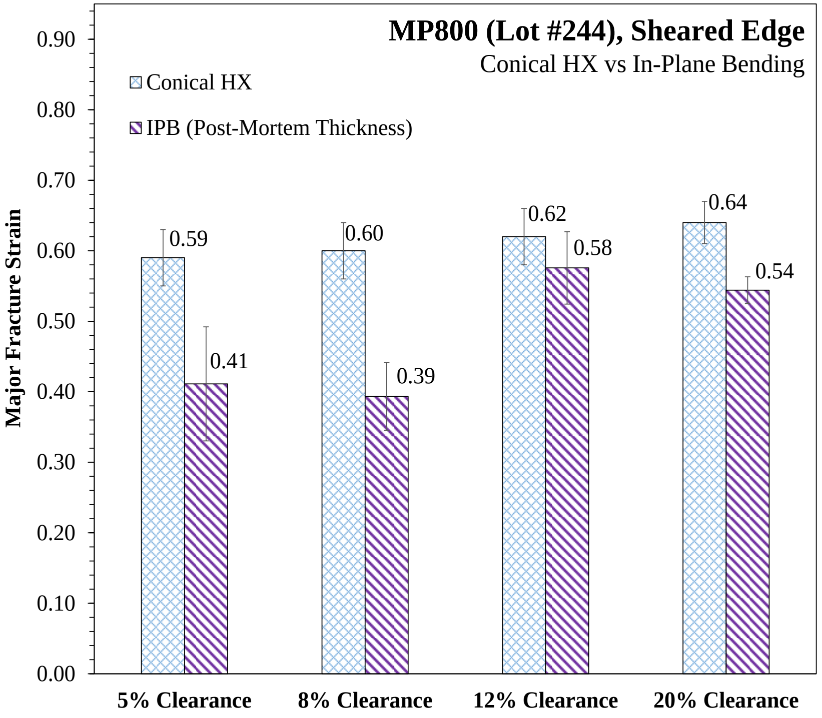
Fracture Strain

$$\varepsilon_3^{IPB} = \ln\left(\frac{t_{crack}}{t_0}\right);\ \varepsilon_1^{IPB} = -(1+R_{90}) \times \varepsilon_3^{IPB}$$

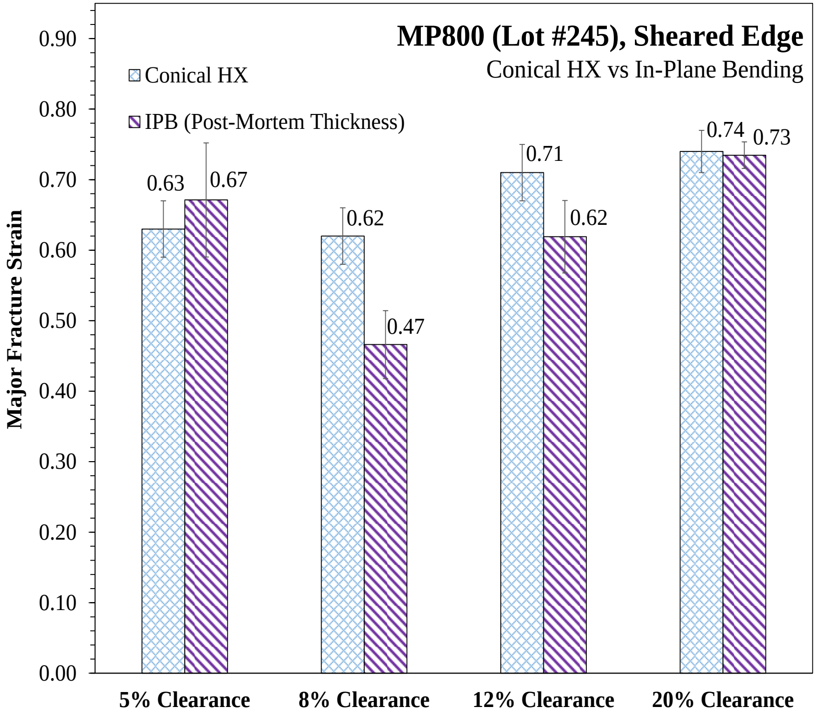
$$R_{90}(MP800\ Lot\ \#244) = 0.76$$

$$R_{90}(MP800\ Lot\ \#245) = 0.80$$

MP800 (Lot #244) Fracture Strains

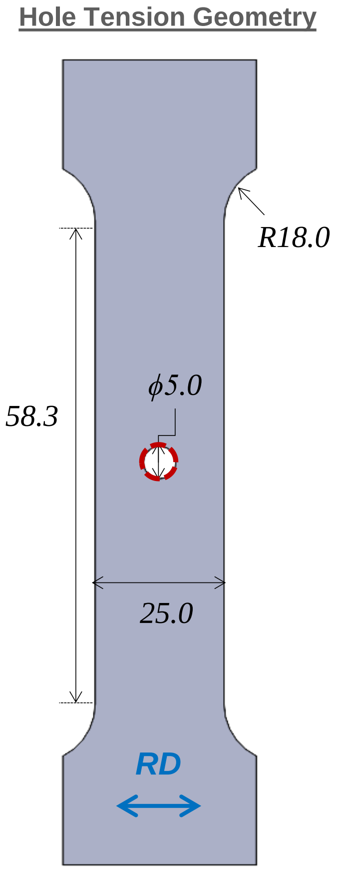


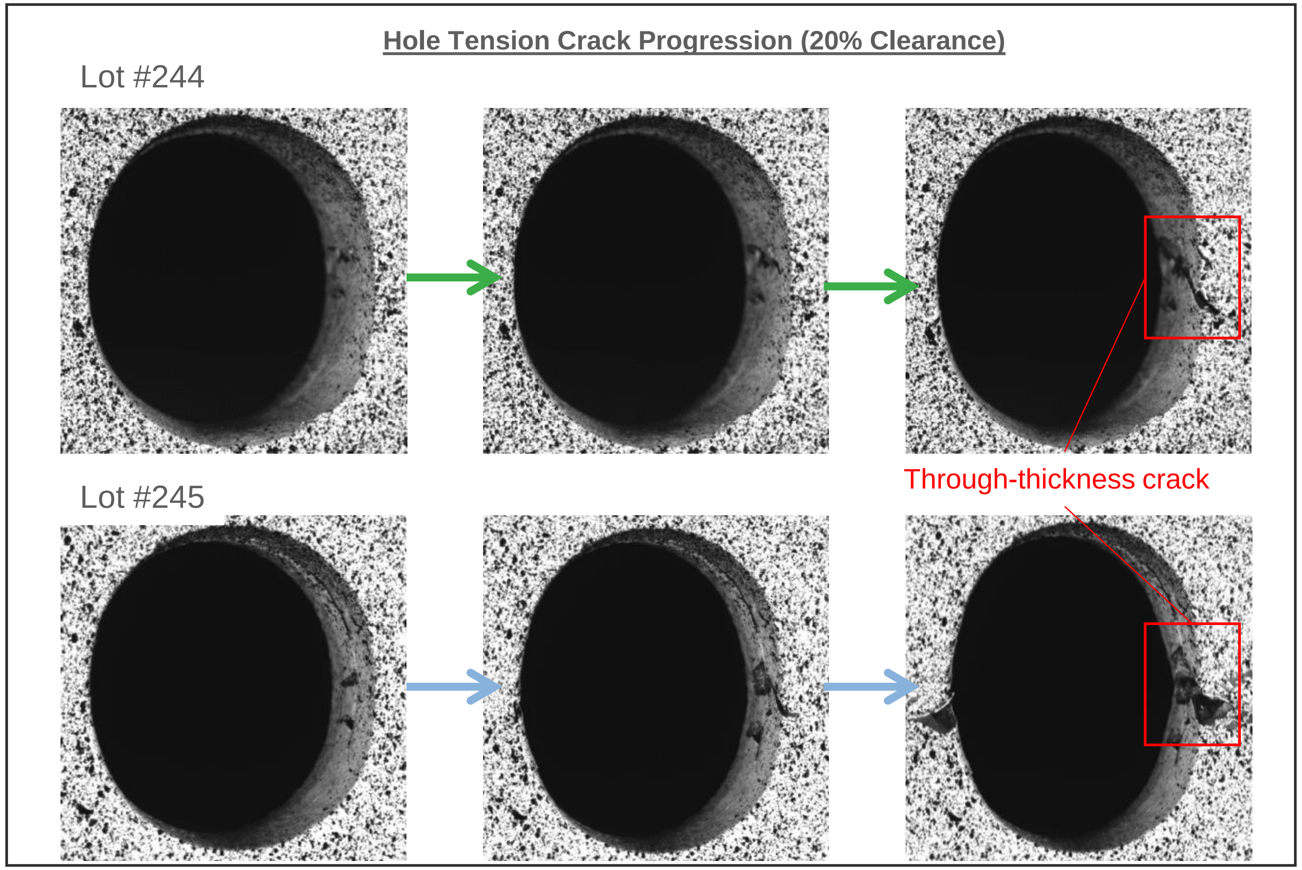
MP800 (Lot #245) Fracture Strains



Hole Tension Test (HTT): 12% Clearance

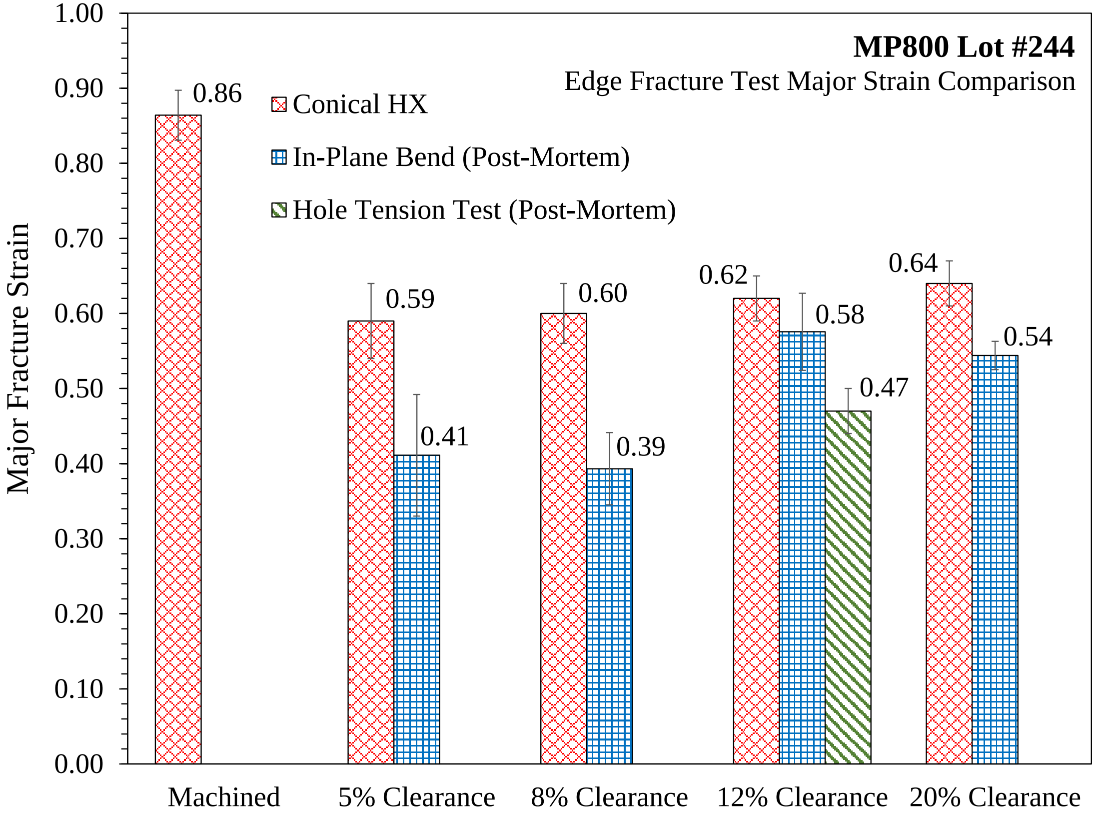
- Unidirectional stretching of the hole. Tests conducted at 12% clearance since centerline cracks were seen in Lot #245.
- **Cracks appear to initiate near the mid-thickness for both materials followed by gradual propagation.**

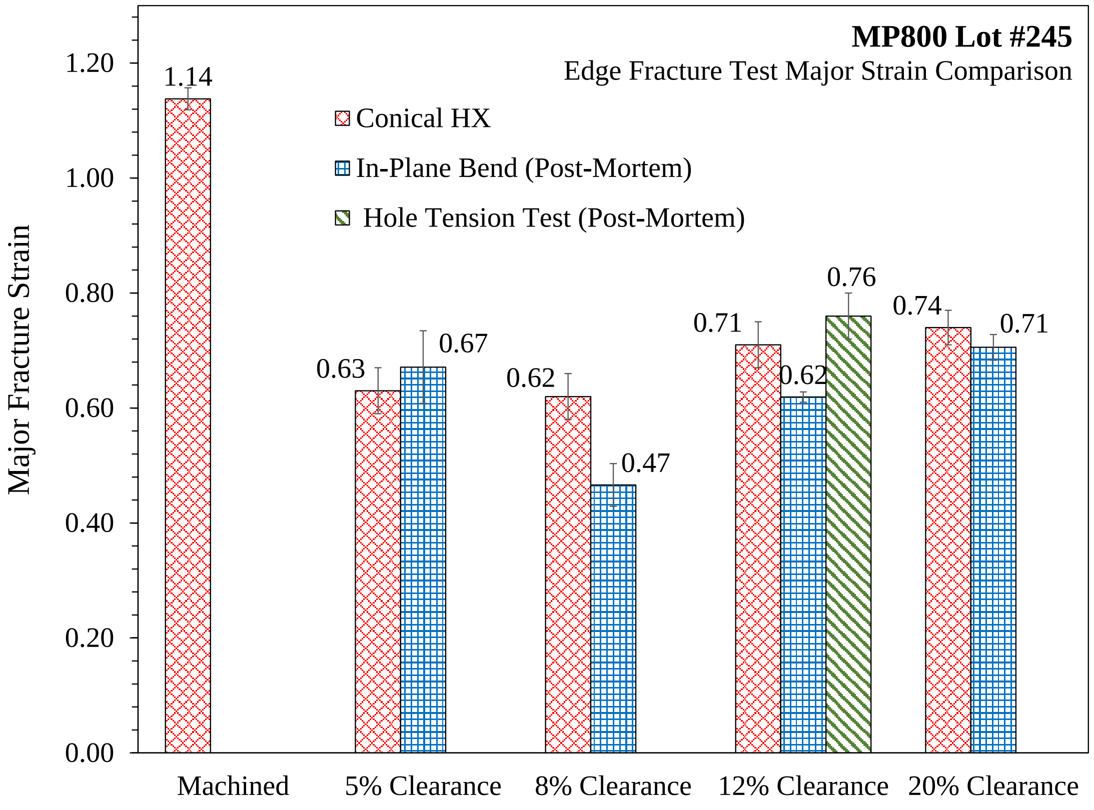




Fracture Strain Summary: Boundary Condition Effect

- HTT fracture strains also measured using post-mortem thickness. Tests compared at through-thickness rupture.
- Hole tension fracture strains similar to conical HX and in-plane bending for Lot #245.
- **Significant sensitivity to test type observed for Lot #244 at 12% clearance. Strong boundary condition effect!**

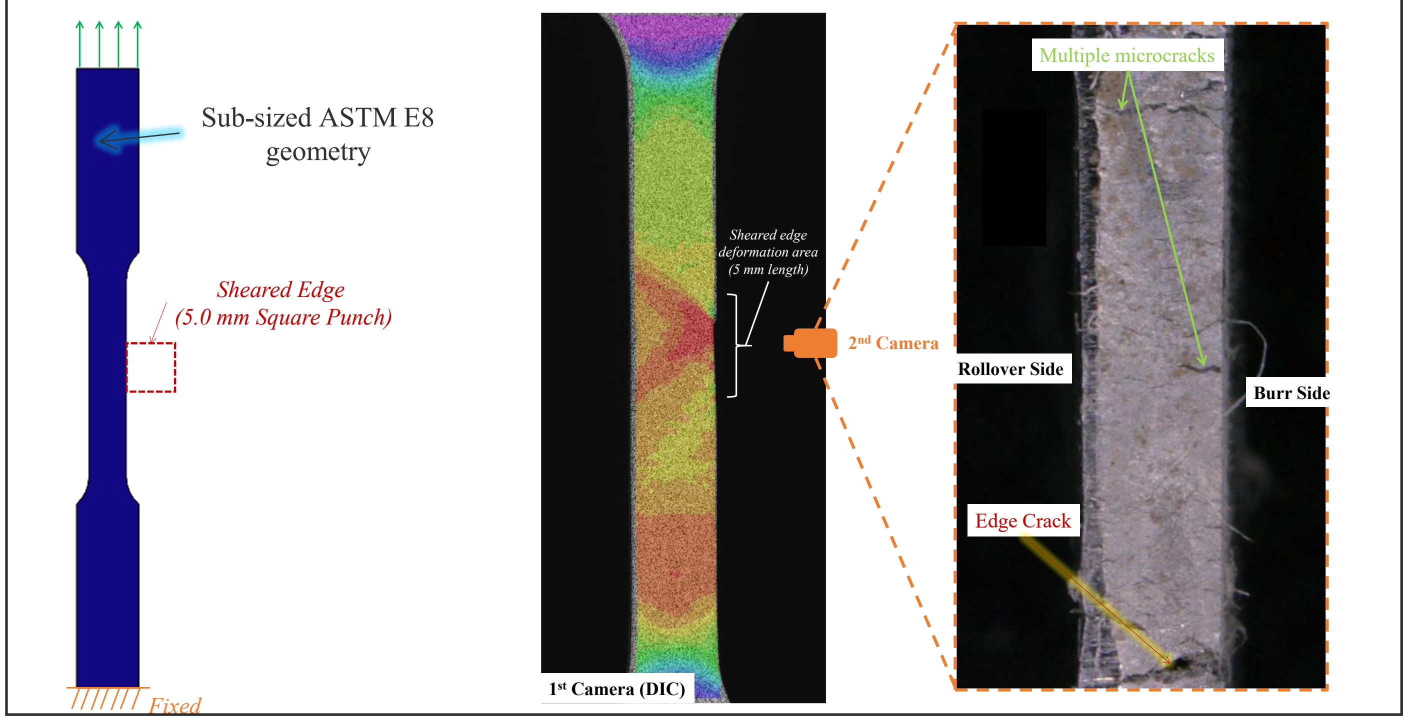




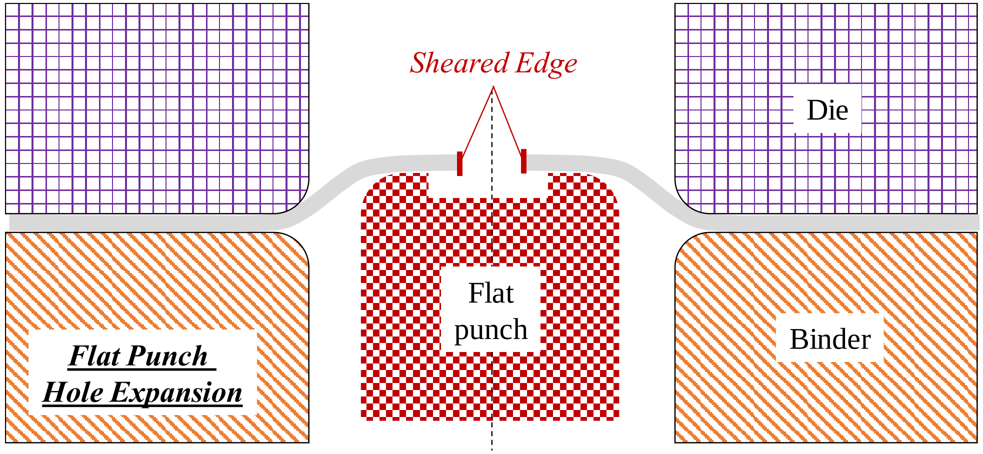
Next Steps on MP800 Edge Stretchability

- Additional clearances such as 2%, 10%, and 30% will be considered for select edge fracture characterization tests.
- Edge fracture tensile test and flat punch HX will be conducted at clearances with lowest and highest edge formability.
- **Output: Assess influence of stress and strain gradients in the SAZ on edge fracture strain at multiple clearances.**

Edge Fracture Tensile Test



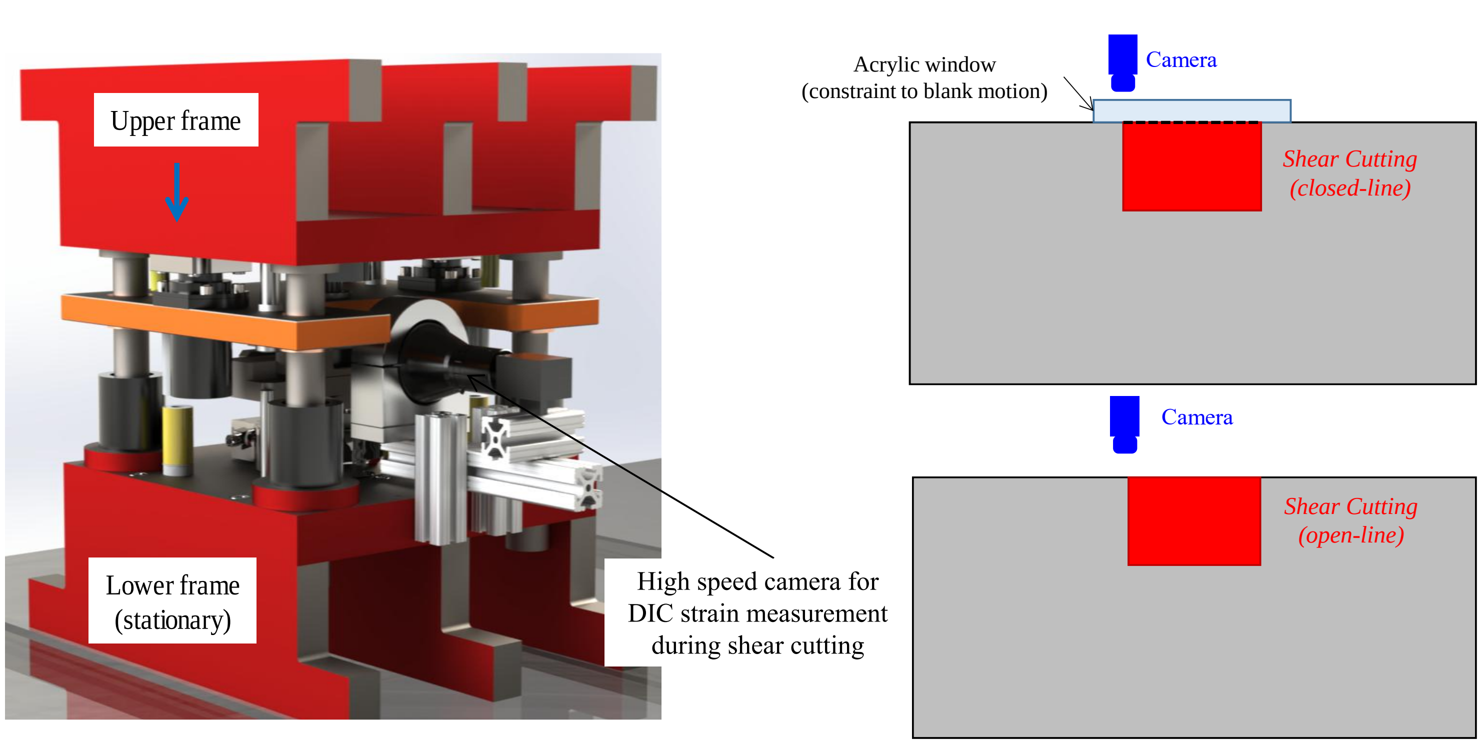
Flat Punch HX Schematic



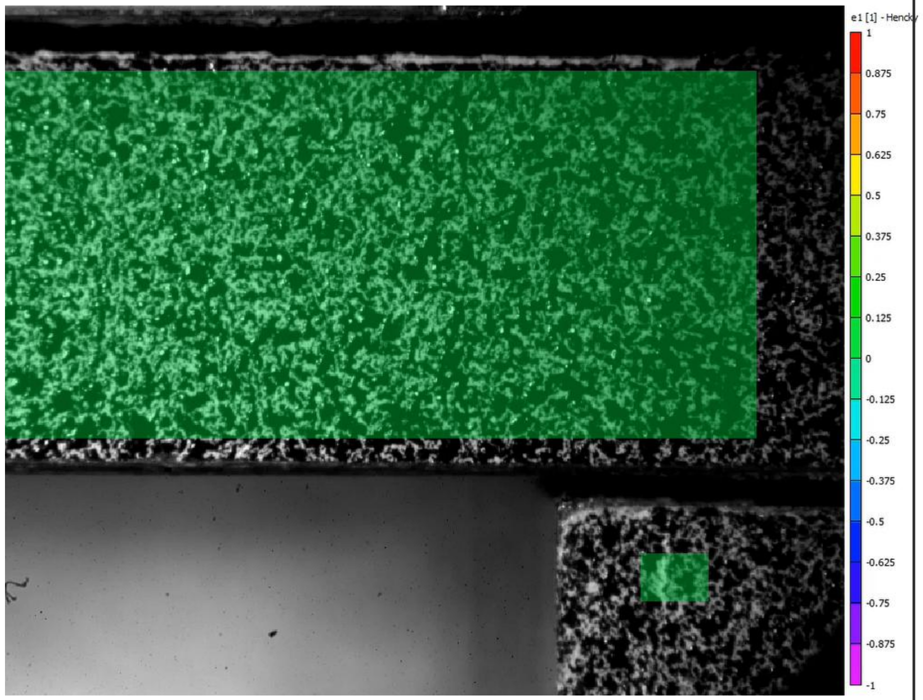
Future Work

- **Influence of trimming vs punching and tool wear on cut edge fissure generation and edge stretchability.**
- Experimental measurement and numerical modelling of strains induced during shear cutting.
- SAZ mapping and evaluation of FE simulations of edge stretching using software like LS-DYNA and Autoform.

Schematic of Through-Thickness Shear Fixture at UW

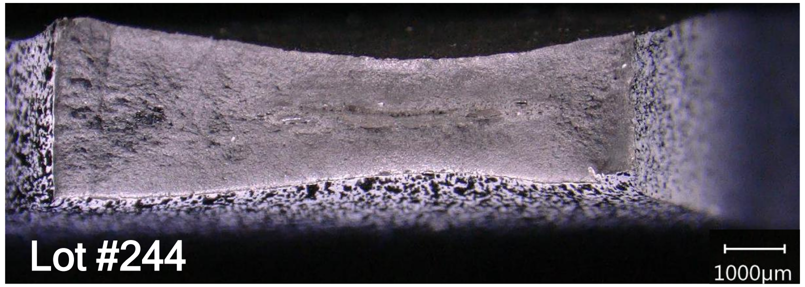


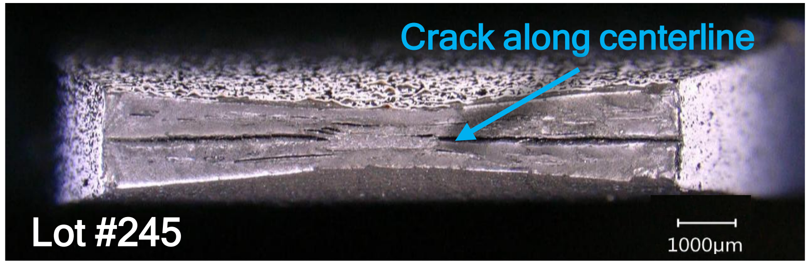
DIC Strain Evolution During Trimming: Lot #244, 5% Clearance

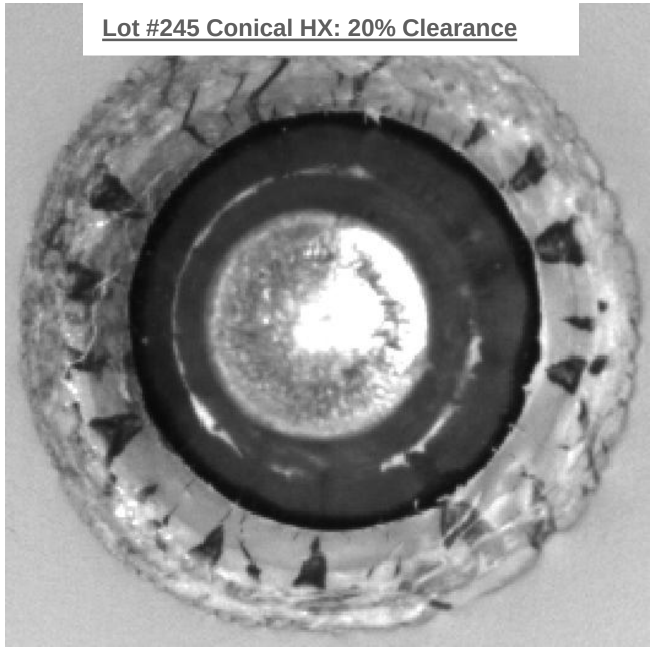


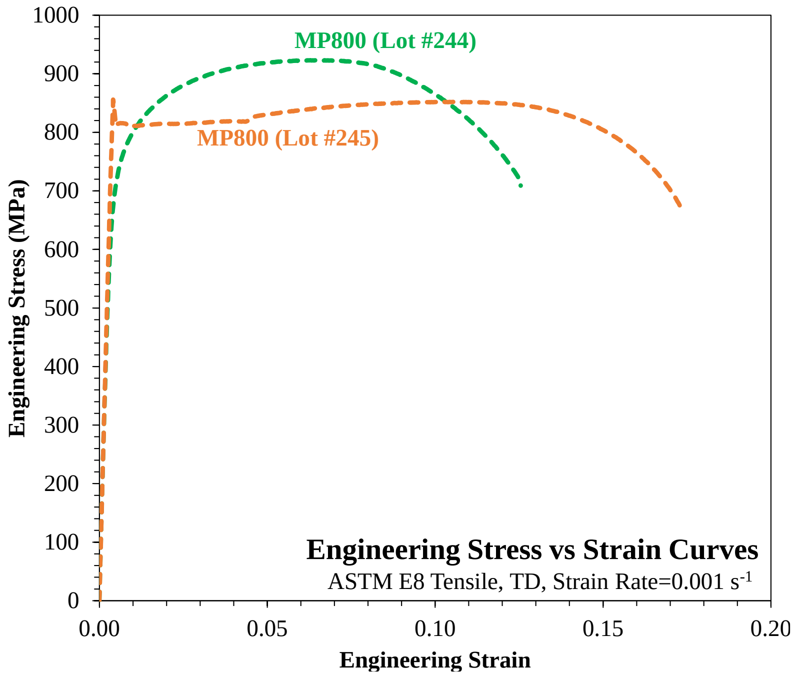
Summary

- Tensile fracture surface and stretching of edges sheared at 12% or higher promoted centerline cracks in Lot #245.
- Lot #245 possessed similar or higher fracture strain than Lot #244 due to its larger elongation and low hardening rate.
- **Strong sensitivity of fracture strains to test type observed in Lot #244. Relatively smaller influence in Lot #245.**



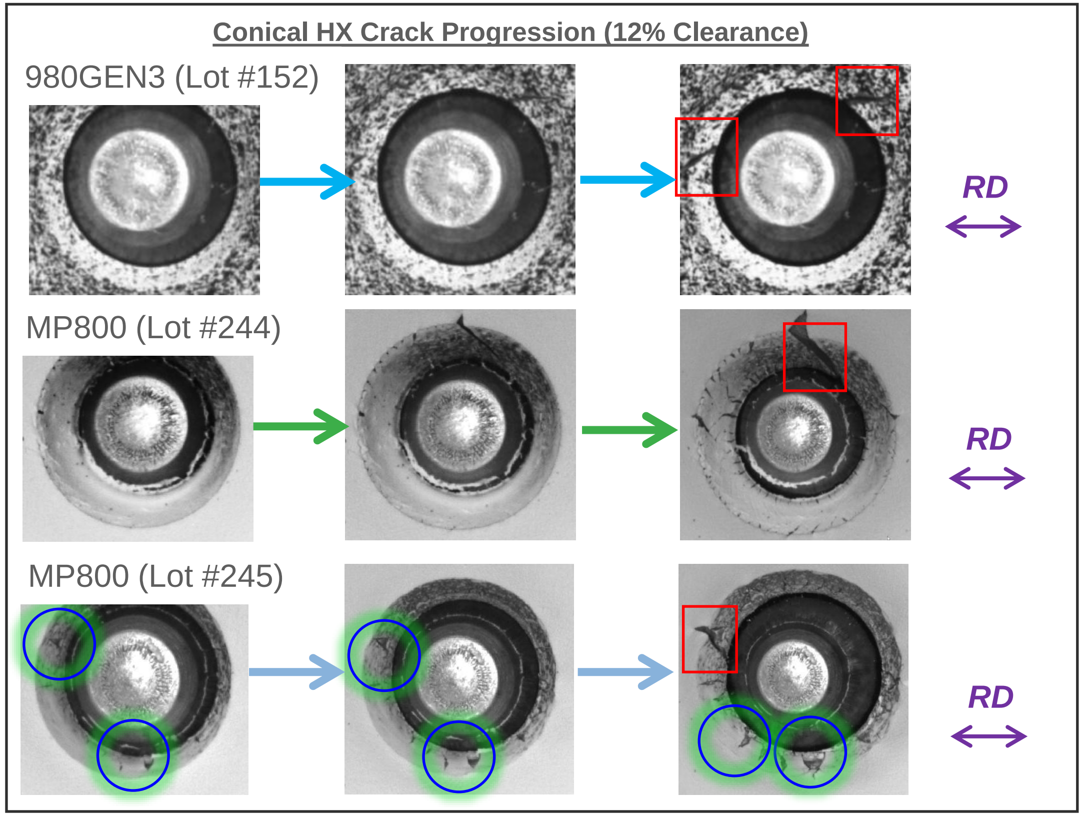


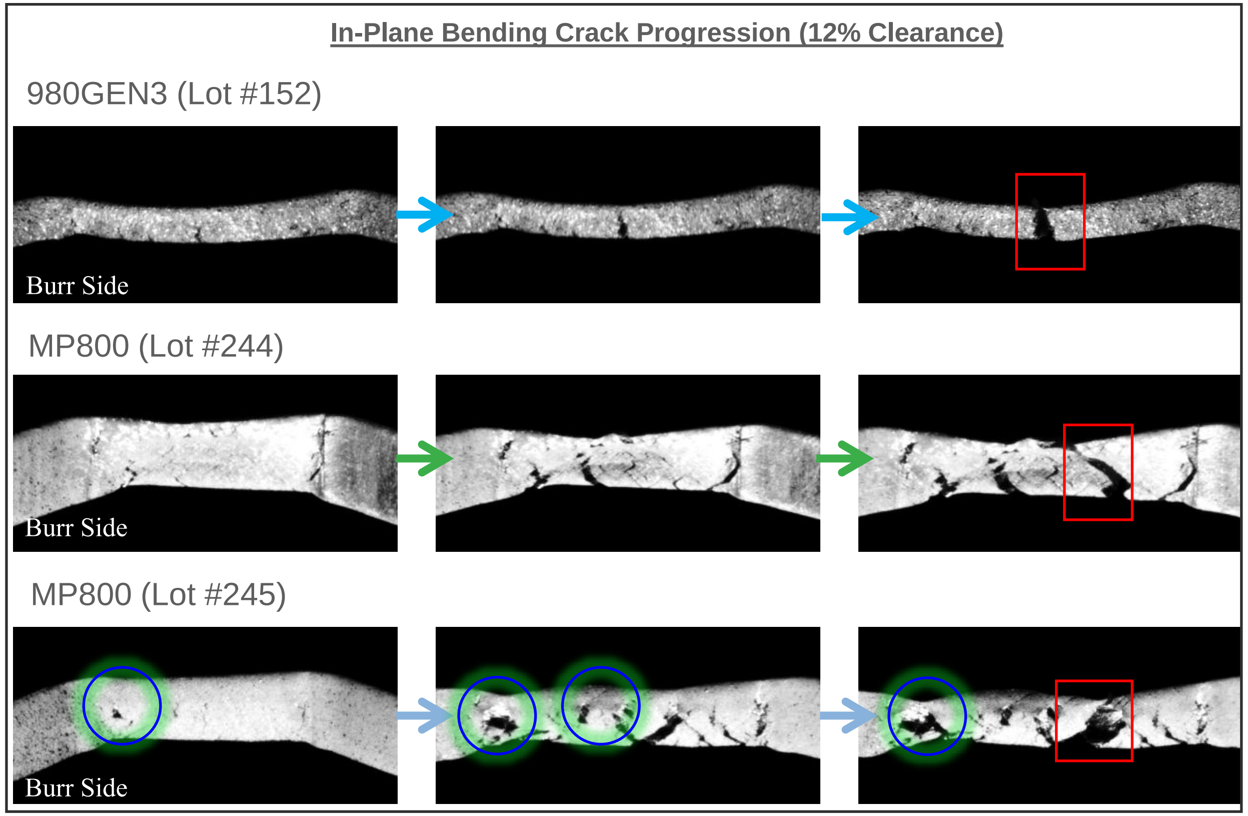




Crack Evolution Comparison with 980GEN3 Steel

- Crack evolution behavior of the two steels contrasted with 980GEN3 having no cut edge fissure at 12% clearance.
- Cracks initiated from tensile edge observed for 980GEN3 steel regardless of the test type.





Crack at centerline/mid-thickness

Through-thickness Crack

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