Development of Dynamic Fracture Criterion for High Strength Steel GMAW HAZ

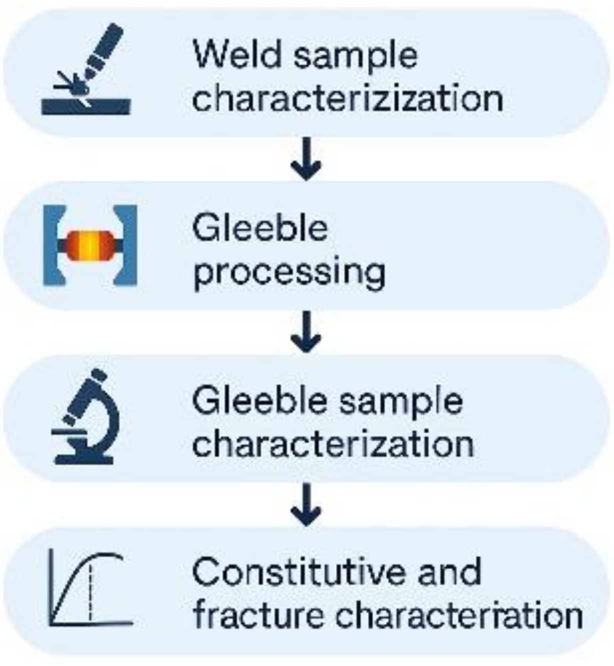
Tae Hwa Lee, Tingting Zhang, Mitra Shabani, Wei Wu, Kathy Wang, Jason Coryell

General Motors

GREAT DESIGNS IN STEEL™

Objective

Recreate the Heat Affected Zone (HAZ) of a Gas Metal Arc Welding (GMAW) in a High Strength Low Alloy (HSLA) steel to characterize its constitutive and fracture properties directly



1. **Weld sample characterization**
   - Lap Shear and T-Joint tests
   - Characterize the HAZ (Optical Microscope microstructure, microhardness, SEM)
   - Determine the target HAZ
2. **Gleeble processing**
   - Explore range of peak temperatures and cooling conditions
3. **Gleeble sample characterization**
   - Hardness and OM microstructure, SEM final condition
4. **Constitutive and Fracture Characterization**
   - 6 miniature geometries to target range of stress-states and strain rates

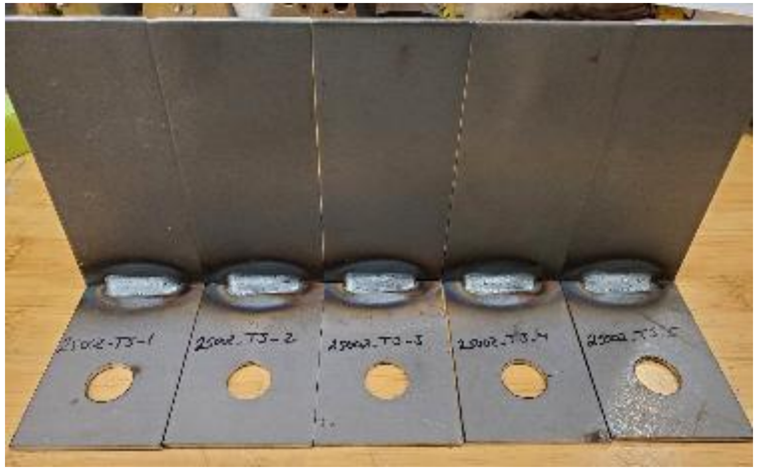
Weld sample characterization overview

1. Testing stack: 2mm HSLA symmetric stack
2. Pull Lap Shear (LS) and T-Joint (TJ) weld coupons
3. Examine microstructure of as-received MIG weld to determine various HAZ regions

   Hardness mapping, OM and SEM imaging
   + Phase identification

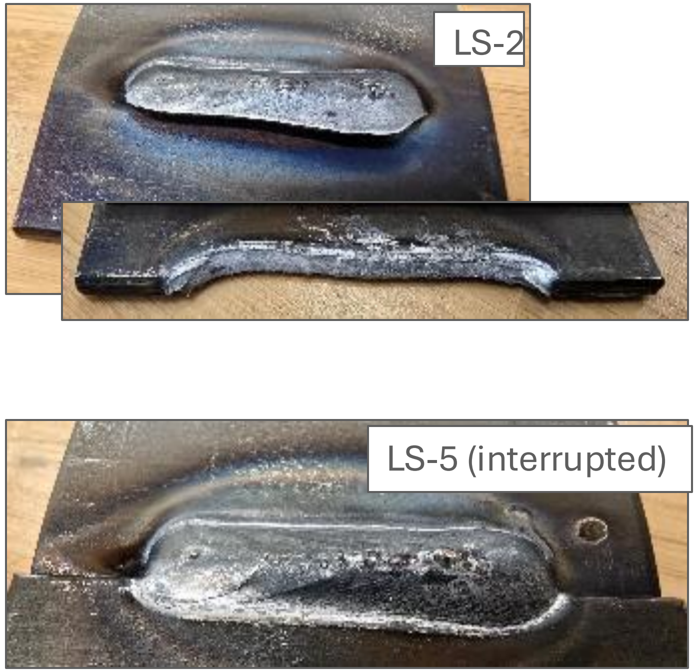
4. Examine microstructure of fractured/interrupted weld coupons to identify HAZ failure initiation

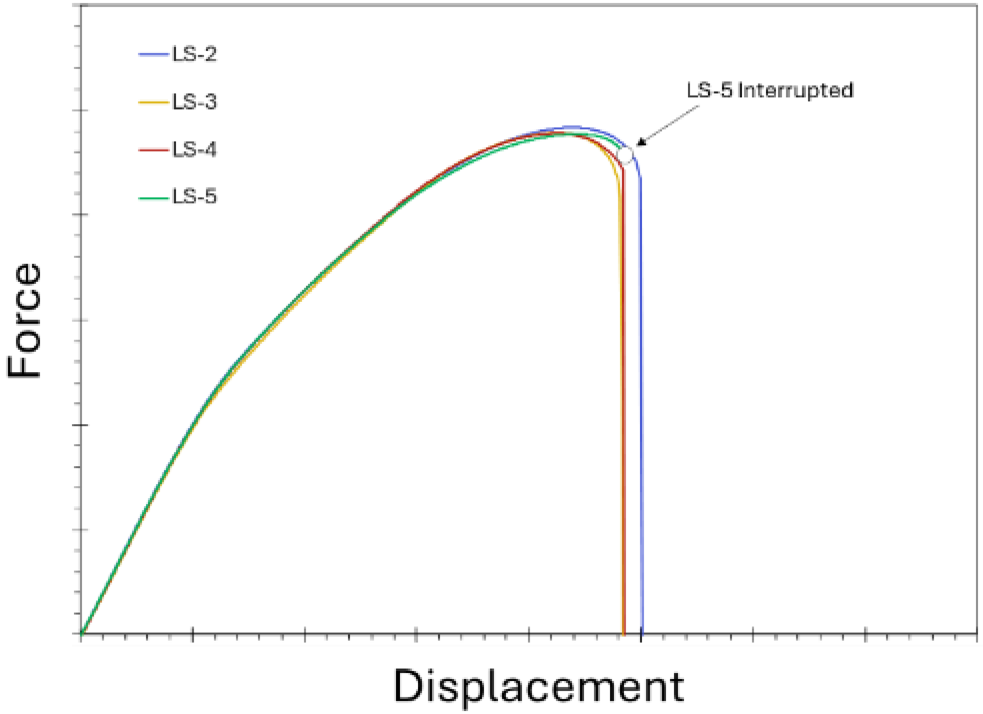
   OM and SEM imaging

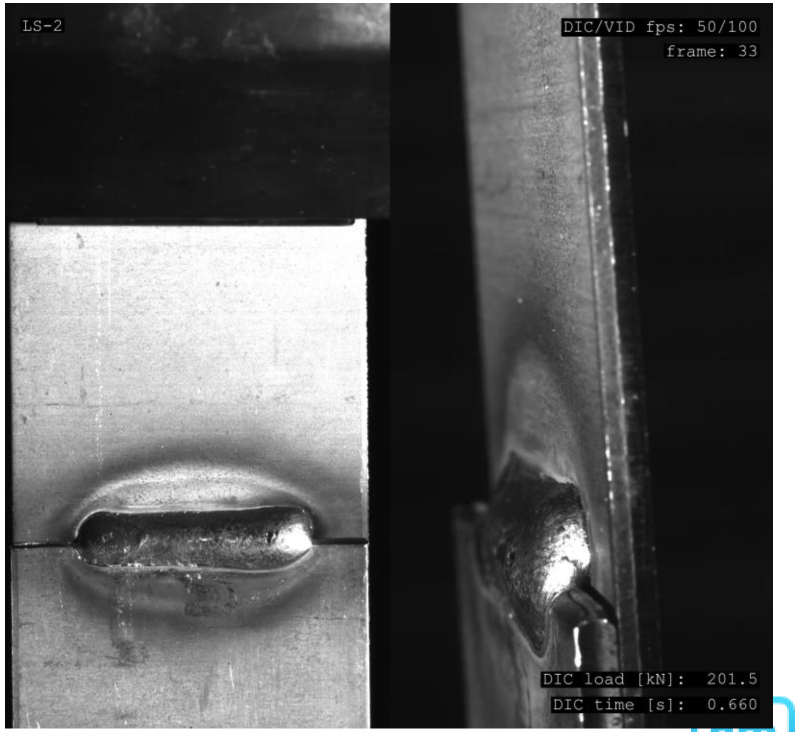


Weld sample characterization
- Lap shear coupon test

- Good repeatability
- Abrupt weld failure after 5-10% load drop
- Failure occurs in HAZ close to weld bead

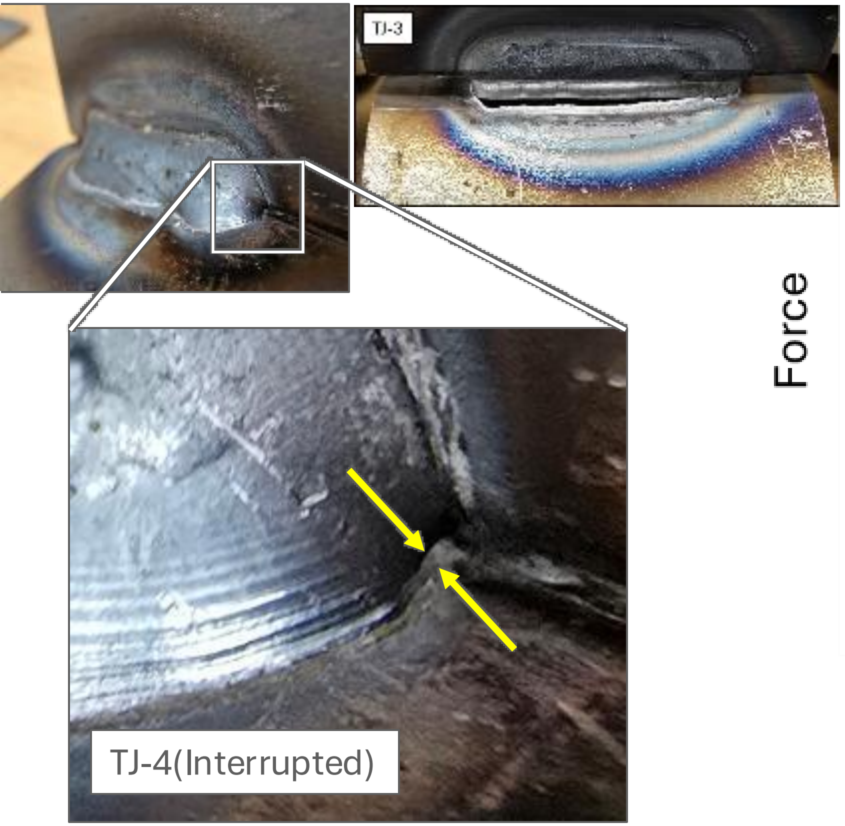


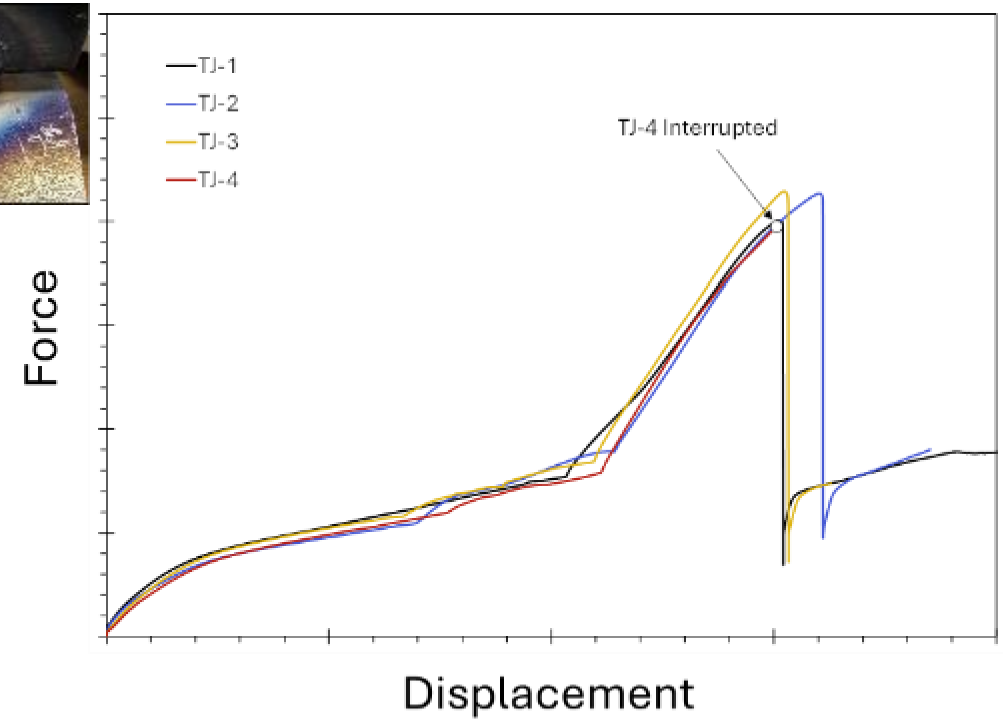


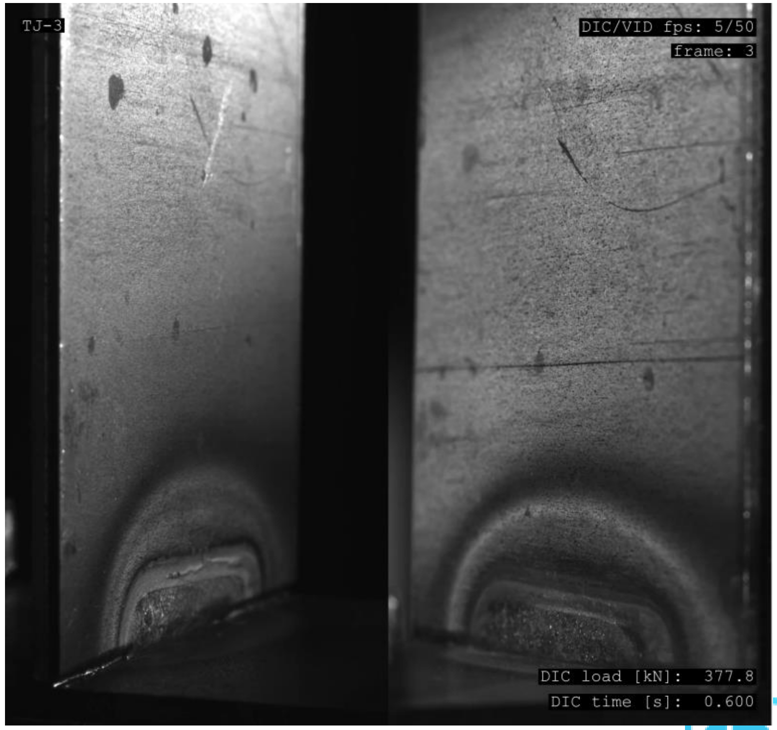


Weld sample characterization
- T-Joint coupon test

- HAZ failure begins from the rear of weld bead
- Fracture propagates toward entire HAZ in Bottom sheet

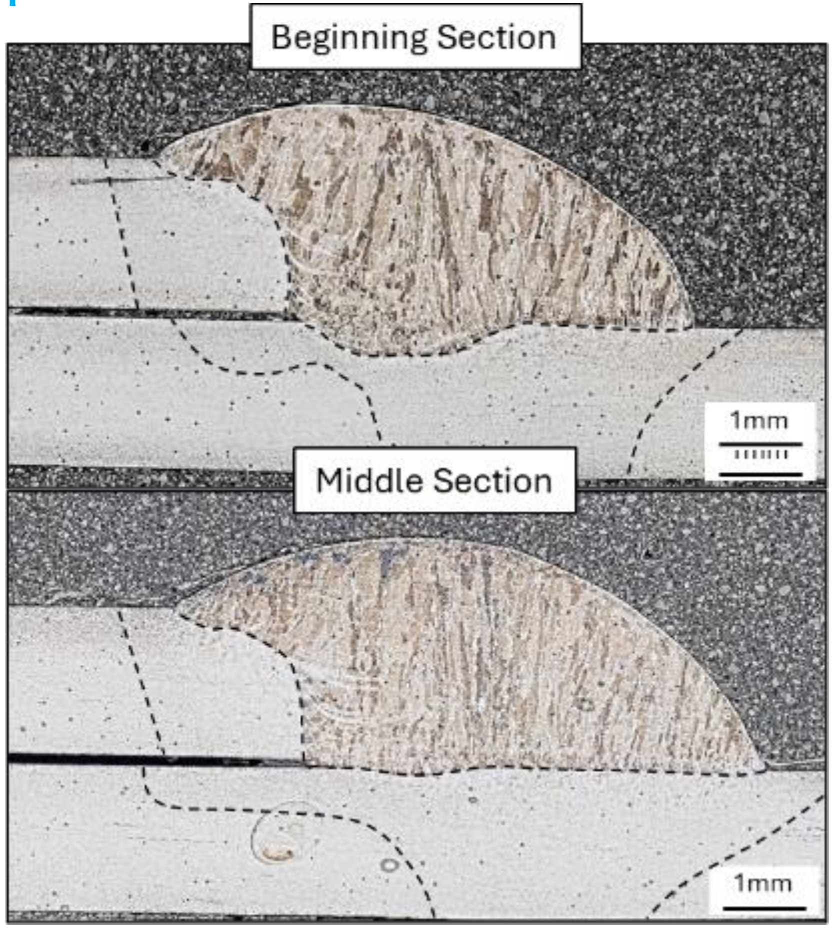


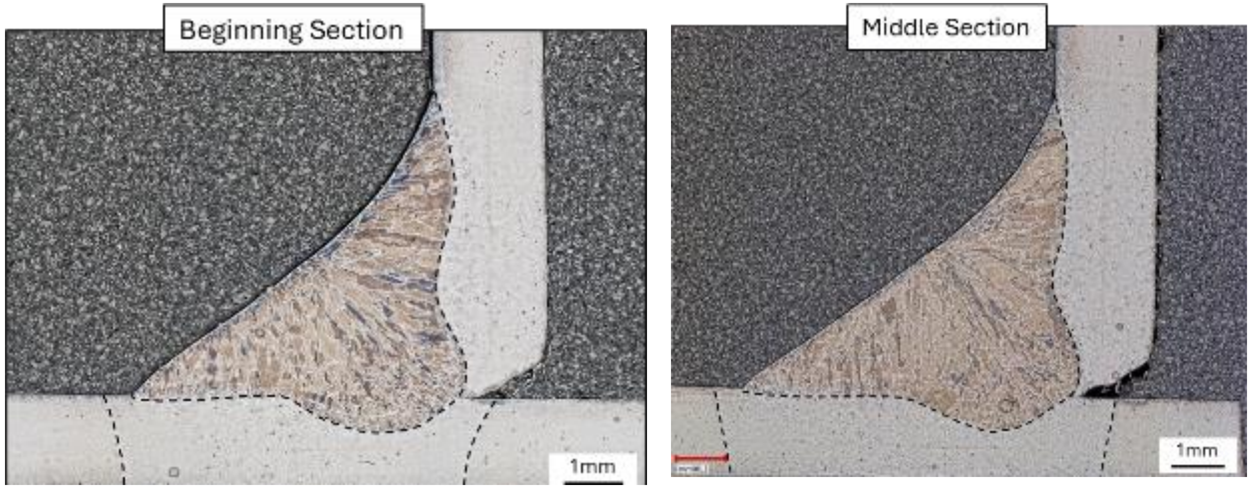




Weld sample characterization
- Microstructure analysis of welded coupon before test

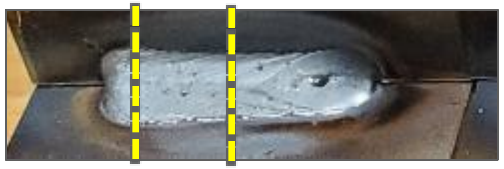
Arc stability and welding parameters stabilize mid-seam, leading to more consistent, shallower penetration. Arc initiation causes transient current and voltage fluctuations, resulting in a higher initial heat input and deeper penetration.





Beginning section Middle section

Beginning section Middle section

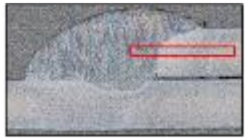


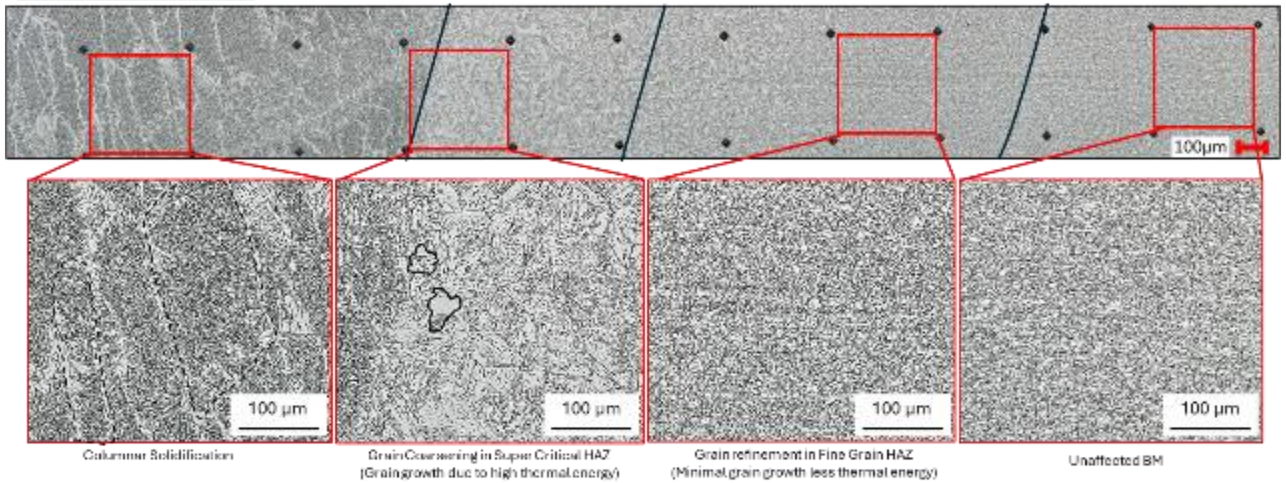
Weld sample characterization
- Optical and SEM micrographs of welded coupon before test

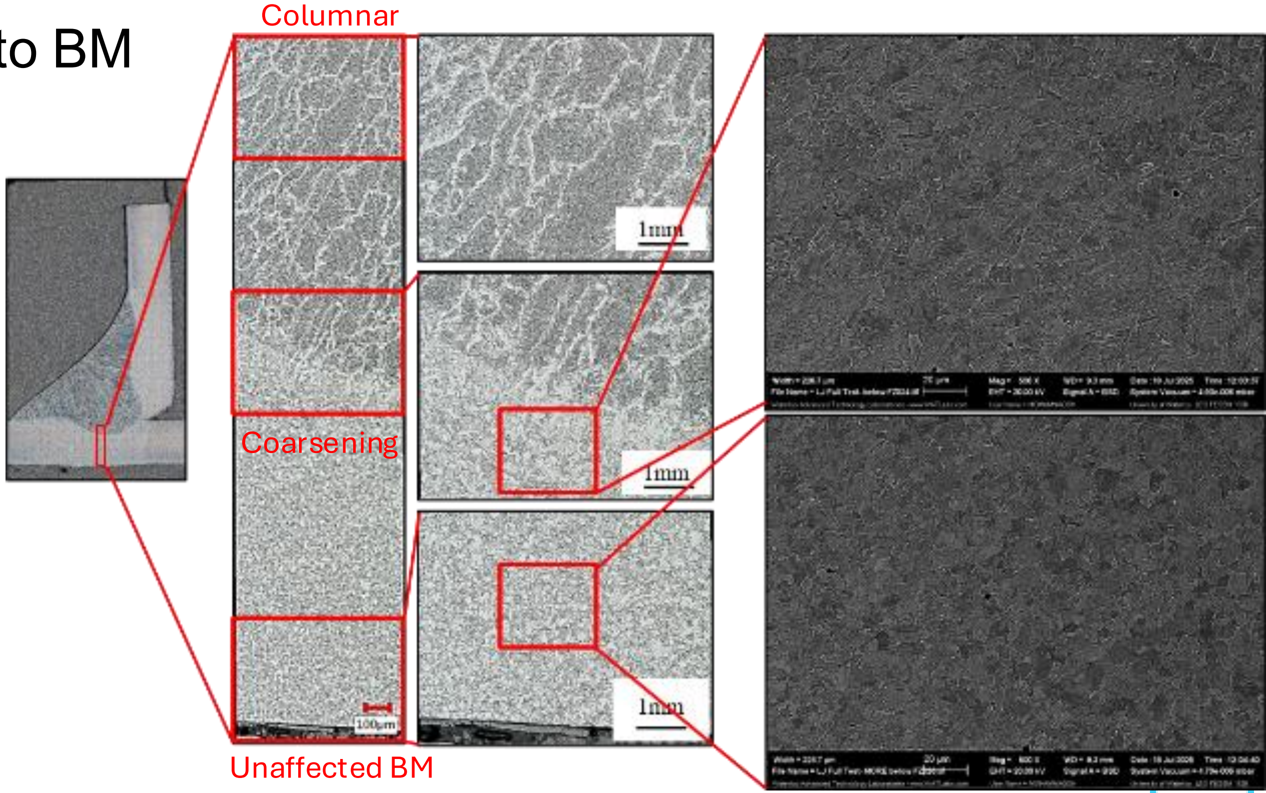
Beginning section

Beginning section

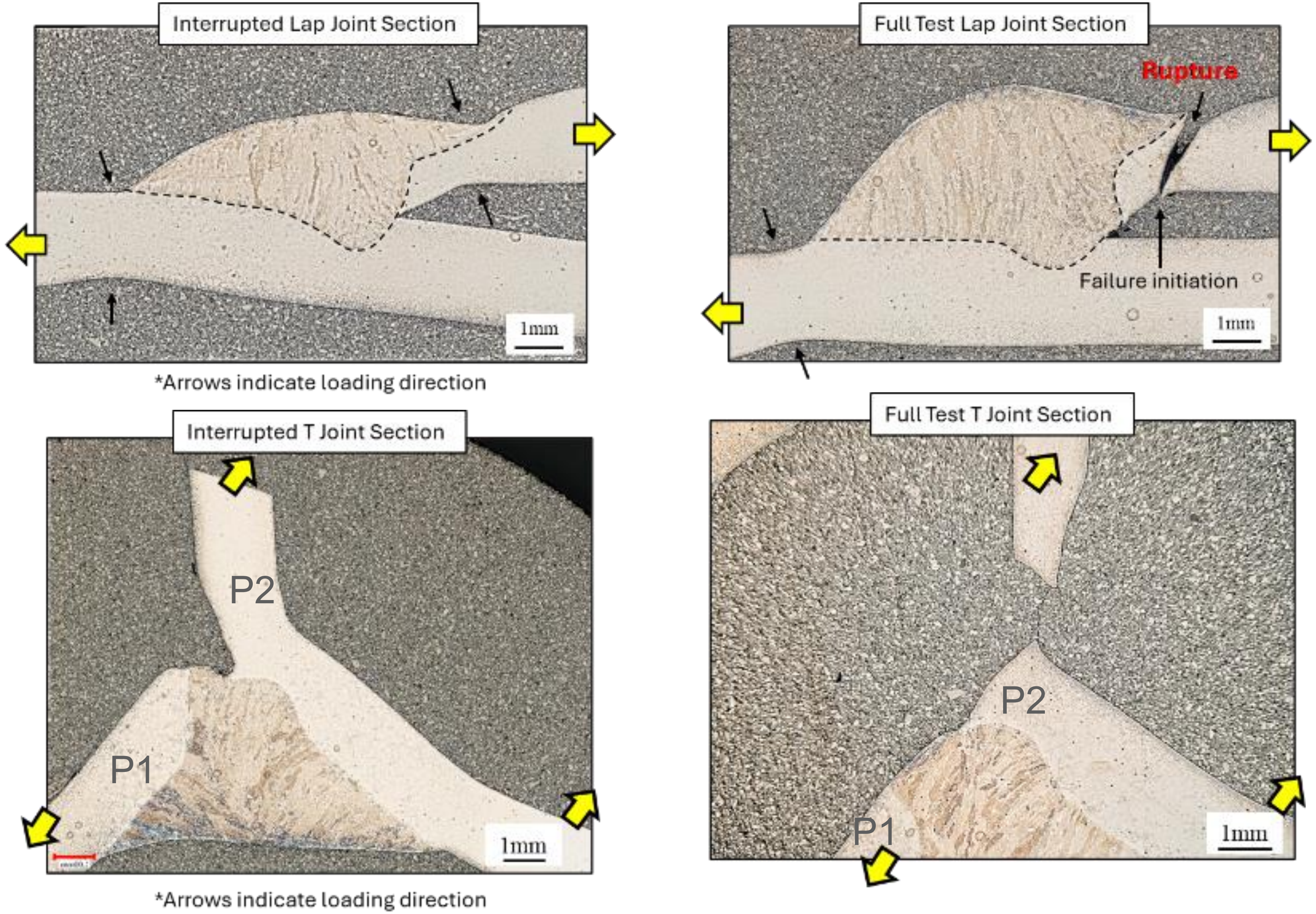
Heterogeneity of microstructure from FZ to BM due to difference in peak temperature experienced in each sub-region:







Weld sample characterization
- Optical and SEM micrographs after interrupted/fractured



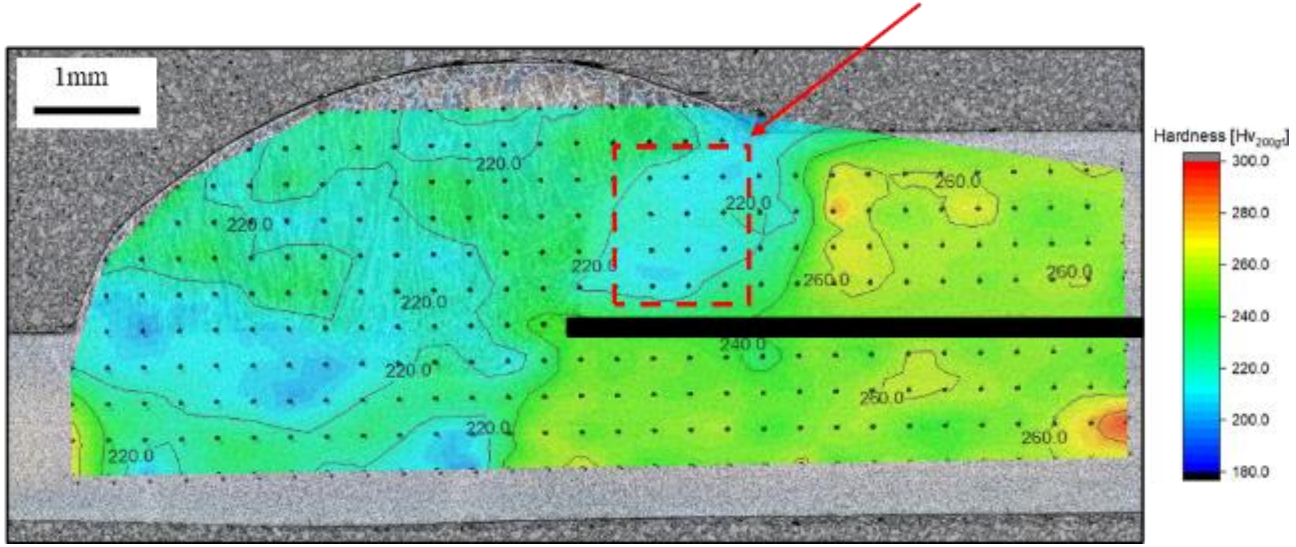
- Results indicate competing necking (indicative of ductile failure behavior) in both the upper and lower sheets
- Final rupture occurred in the upper sheet within the HAZ (Seam remained intact)
- Failure in the Coarse Grained HAZ adjacent to the weld bead

- Ductile failure in the bottom leg of the joints in the Coarse Grained HAZ adjacent to the weld bead

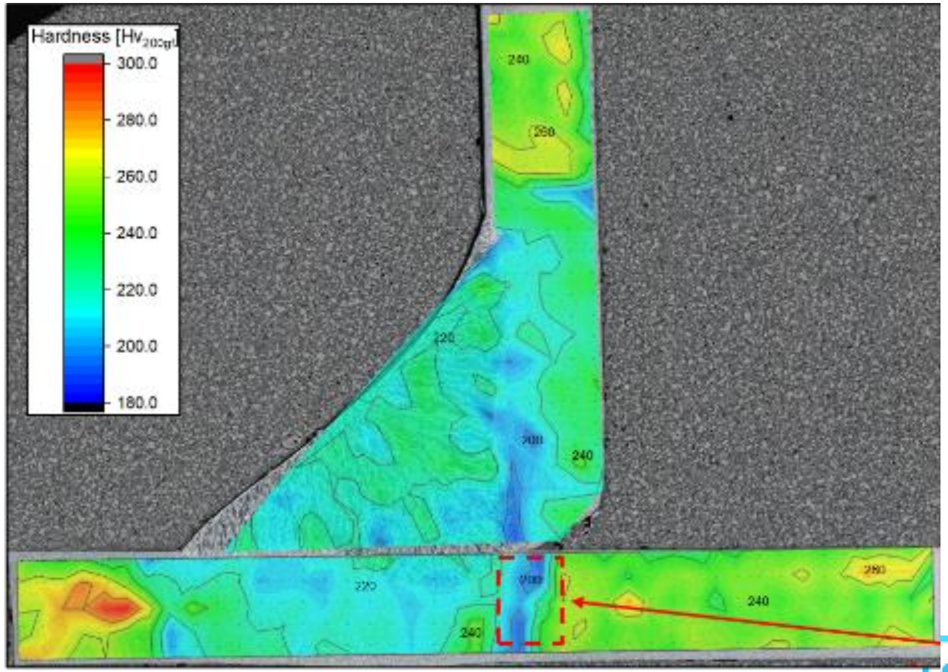
Weld sample characterization
- Microhardness map

- Hardness mapping performed on "Beginning" slice location
- Softened region outside of Bead due to significant grain coarsening and boundary strengthening loss
- Failure initiation (strain localization) region in shear loading
- Target hardness for Gleeble simulation should be ~200 to 220 Hv

- Hardness mapping performed on "Beginning" slice location
- More severely softened Coarse Grained HAZ compared to the Lap Joints
- Factors such as geometry, heat input, and volume of the bead directly affect heat dissipation trends and HAZ softening severity



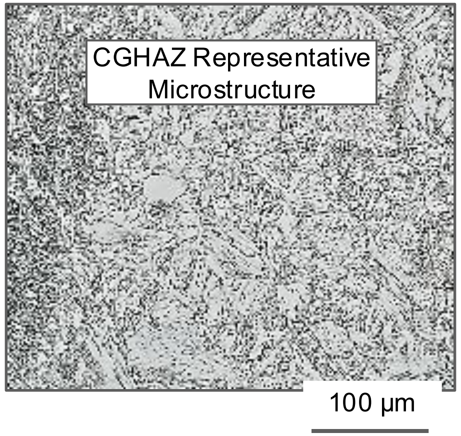
Lap Joint



T Joint

Weld sample characterization
- Weld testing and analysis summary

- Both Lap Joint and T-Joints revealed the coarse-grained HAZ as the failure initiation region
  - Hardness of the CGHAZ: 200-220 HV
  - Hardness of the BM: 240-260 Hv
  - Hardness of the FZ: 230 Hv



- The softening in the CGHAZ is likely due to loss of grain boundary strengthening
- Softening was more severe in the T-joint geometry due to presumed higher volume of the filler metal used in this geometry and higher overall heat input
- Gleeble Thermomechanical simulations will aim to simulate the CGHAZ microstructure

Gleeble processing

1. Validate Gleeble processing parameters

    Ensure target temperature is achieved and identify thermal gradient (multiple TC’s)

2. Process coupons for target temperature, dwell time, cooling period

Loop steps until Hardness and OM imaging matches CGHAZ

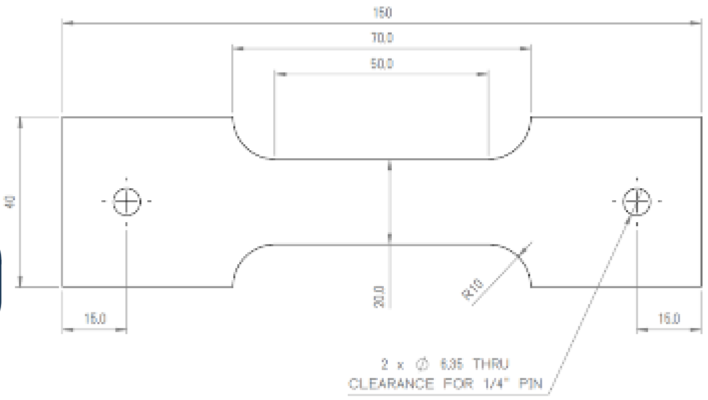
3. Microhardness and OM specimen

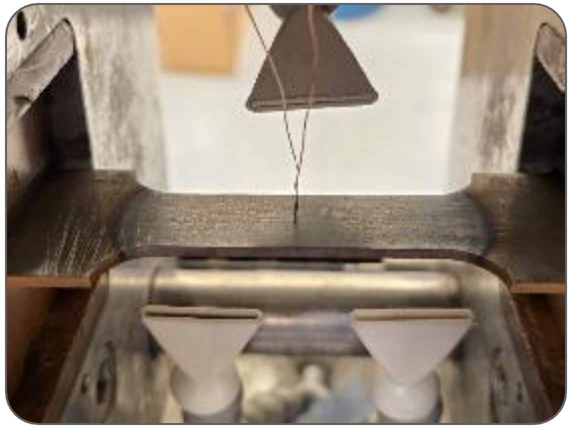
    Check if resulting microstructure is close to target

4. Final SEM verification for matching microstructure to target ‘Coarse-Grained’ HAZ

    Phase identification,
    Phase quantity counting

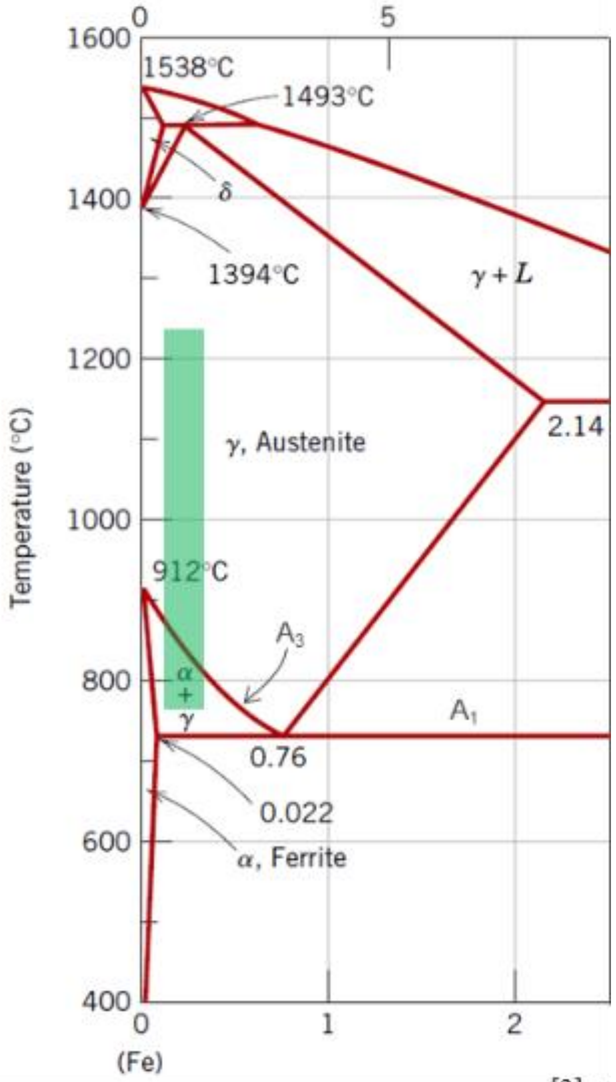
5. Bulk produce Gleeble coupons for Fracture Coupon extraction





Gleeble heat processing parameters

- Ideal C-Fe binary diagram, using approximate C = 0.2 wt%
  - < A1 = 727°C → α, Ferrite
  - A1 to A3 = ~880°C → α, Ferrite + γ, Austenite
  - A3 to ~1500°C → γ, Austenite
  - > ~1500°C → Liquidus
- Target temperatures
  - T1 Less than A3
  - T2 Greater than A3
  - T3 Closer to melting temperature
- Cooling rates
  - Natural cooling due to convection in still air and conduction towards cooled grips
  - Forced air quench at low pressure
  - Forced air quench at high pressure



[3]

[1] W. D. Callister and D. G. Rethwisch, *Materials Science and Engineering : an Introduction*, 8th ed. Hoboken, New Jersey: John Wiley & Sons,

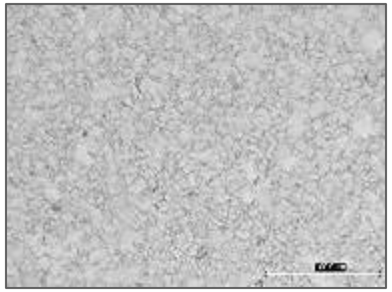
Hardness results and optical microscopy images after final greeble parameters

- Peak T3-100°C, increasingly more grain growth than lower peak temperatures

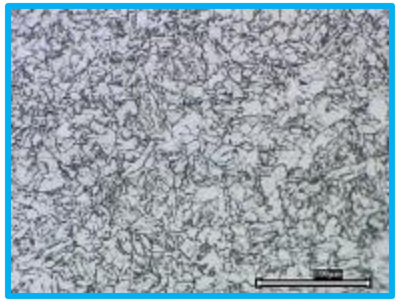
  Similar morphology to lower peak temperatures, matches HAZ seen in ‘refinement’ zone

- Peak temperature T3, more grain growth and faster cooling shows most similar structure to target CGHAZ

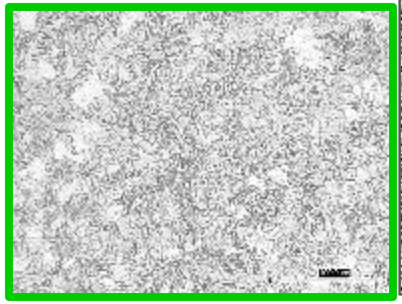
T3-100°C
Air Quench2

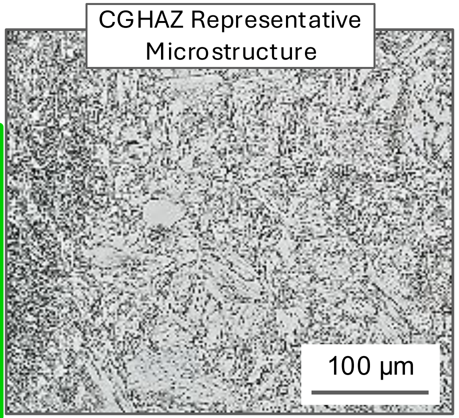


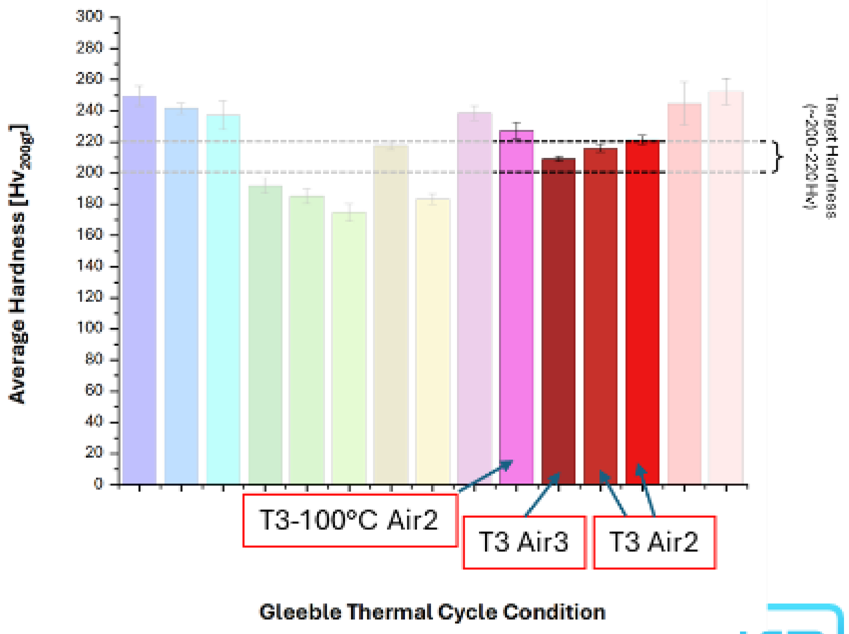
T3
Air Quench2



T3
Air Quench3

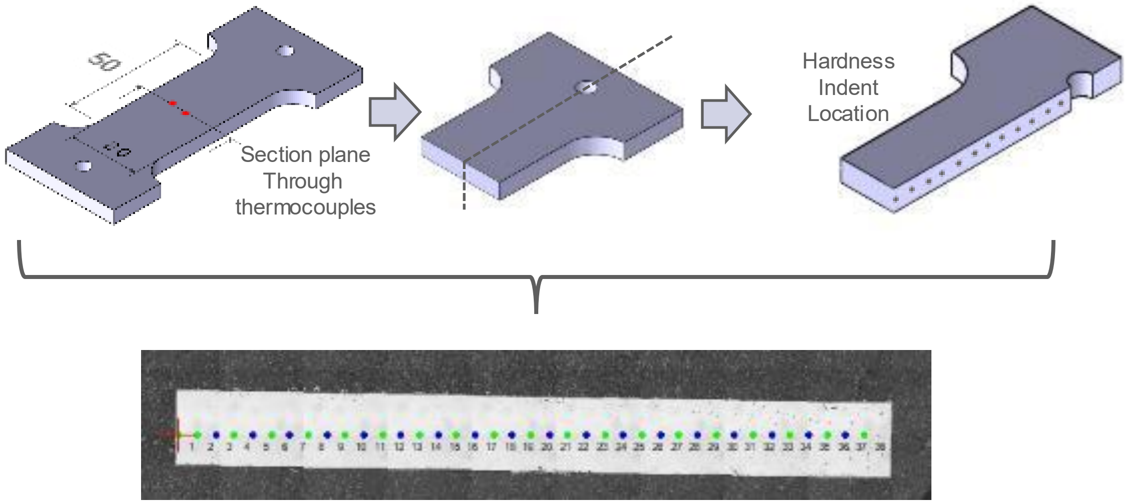




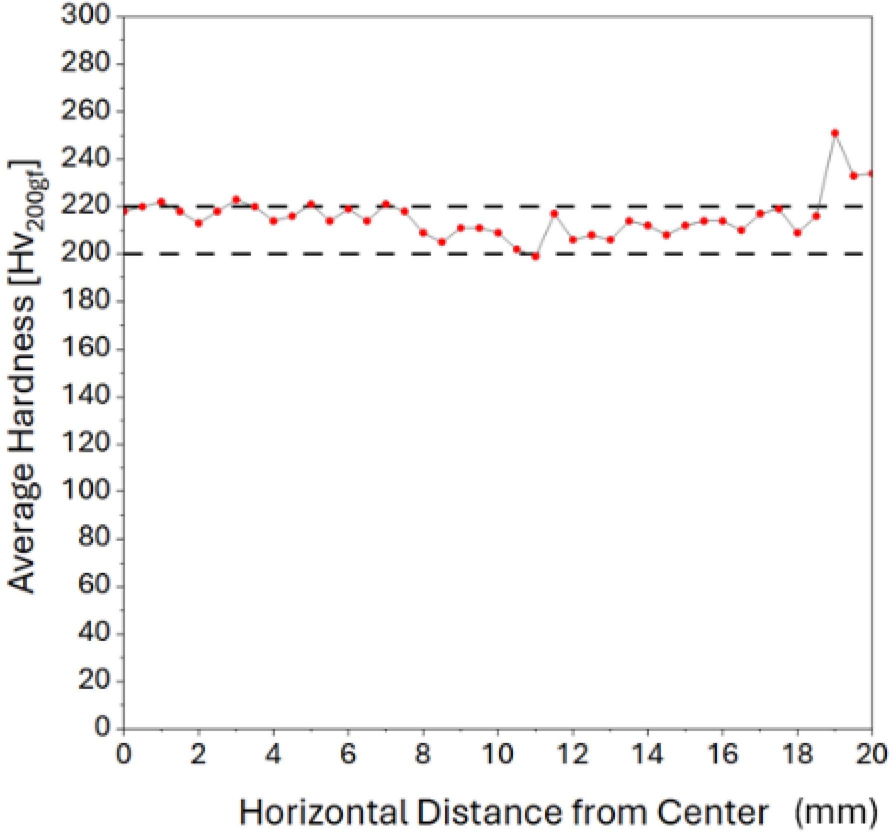


Horizontal hardness measurement

- ~40 mm of usable horizontal distance for fracture characterization coupons
  - Tensile specimen requires 15mm for the, all others require less

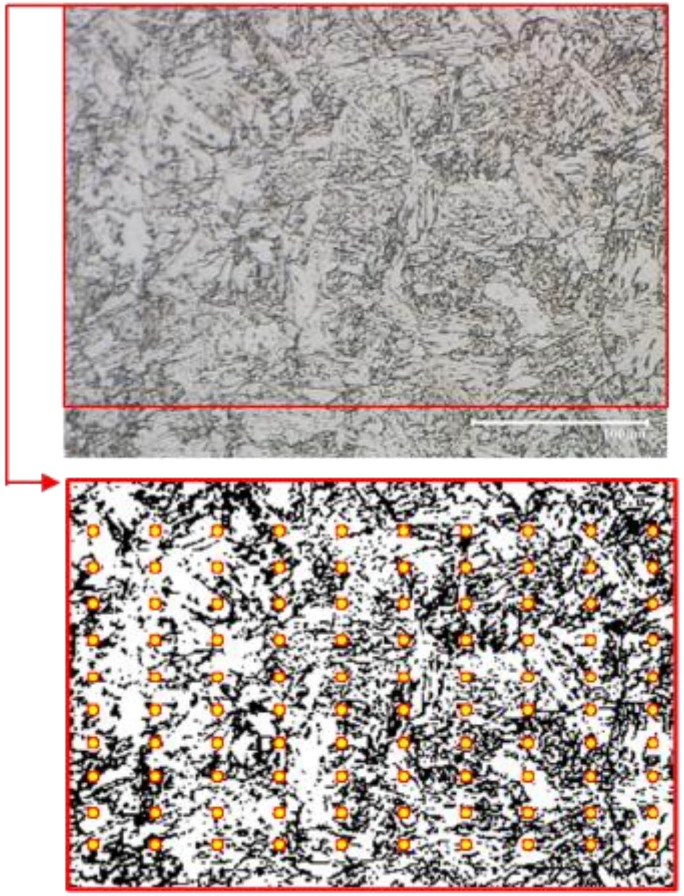


- 38 indents were made covering approximately 20mm, from the center
- Distance between indents: 500 µm
- Load 200 gf



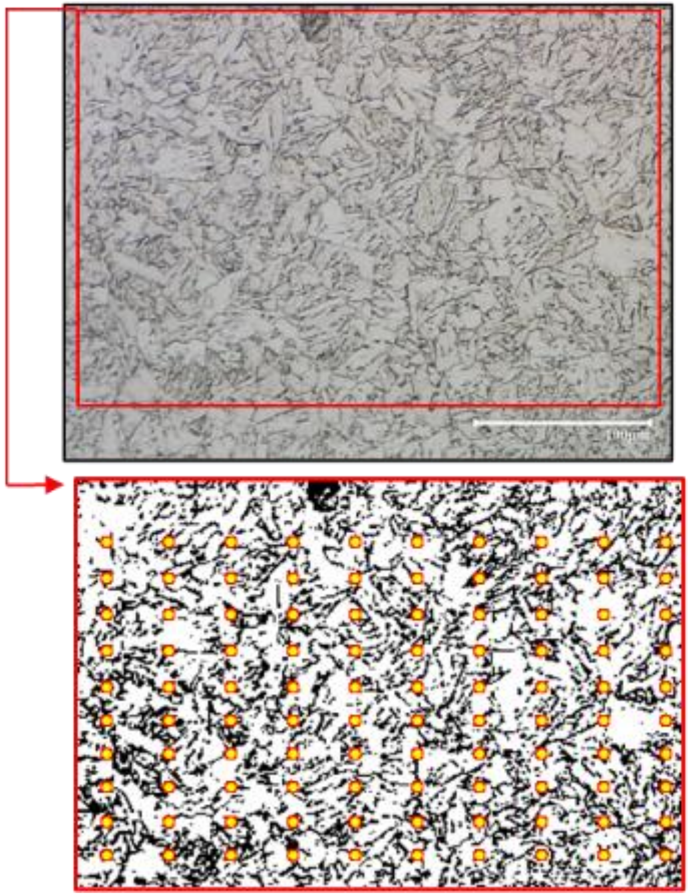
Comparison of phase volume fractions

MIG CGHAZ (1000x)

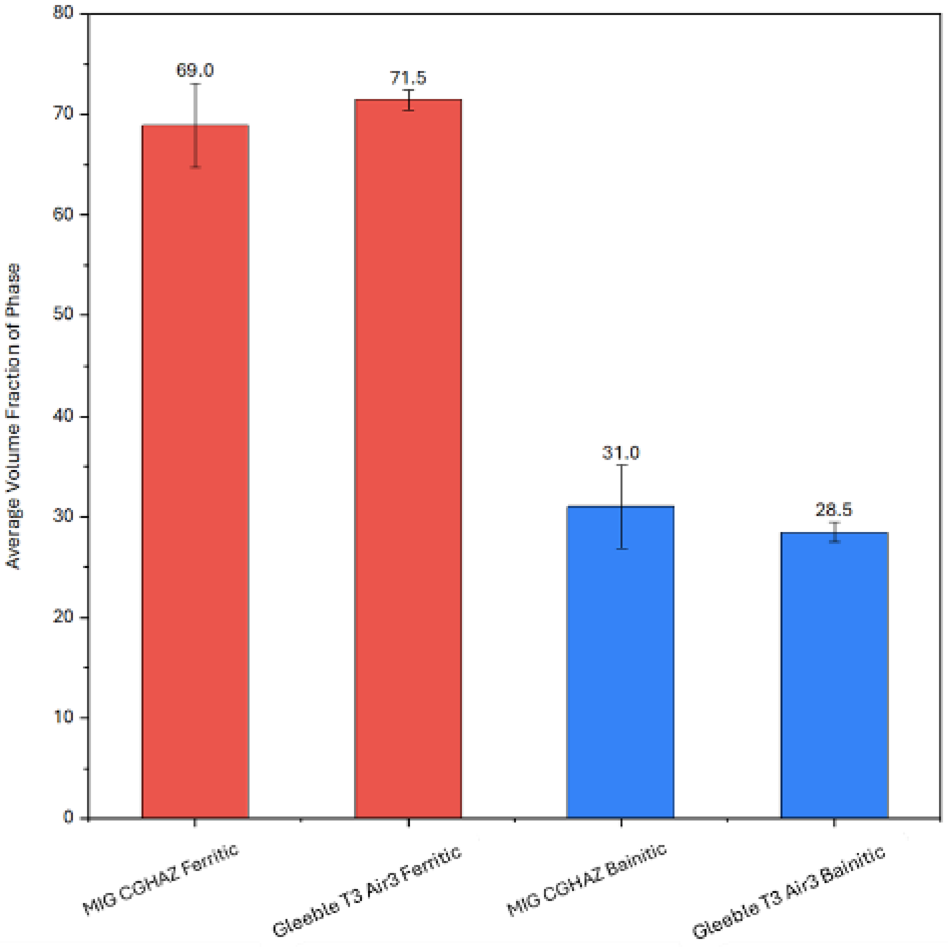


69.0 %Area Ferritic (white phase)
31.0 %Area Bainitic (Black phase)

Gleeble CGHAZ (1000x)



71.5 %Area Ferritic (white phase)
28.5 %Area Bainitic (Black phase)

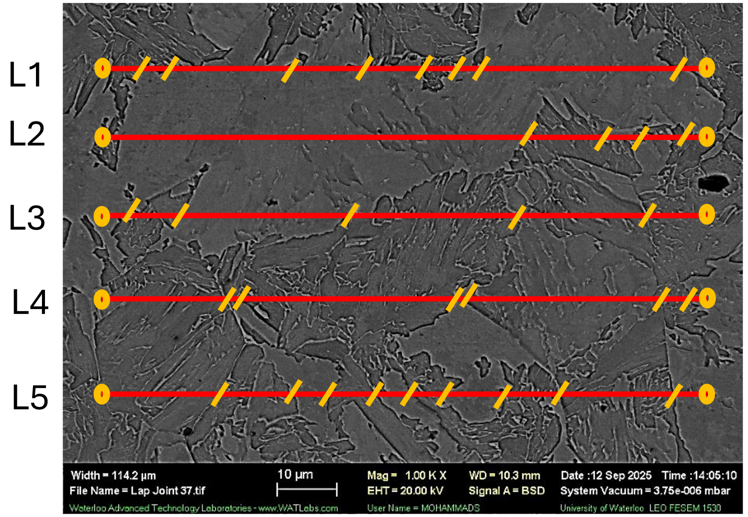


*Error bars are 95% Confidence Intervals from 3 separate measurements

Comparison of grain sizes

MIG CGHAZ

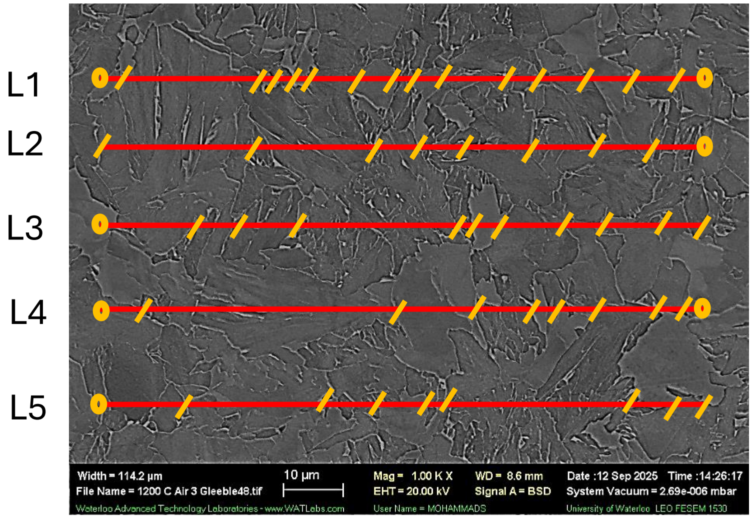
Total length of segment : 100 µm



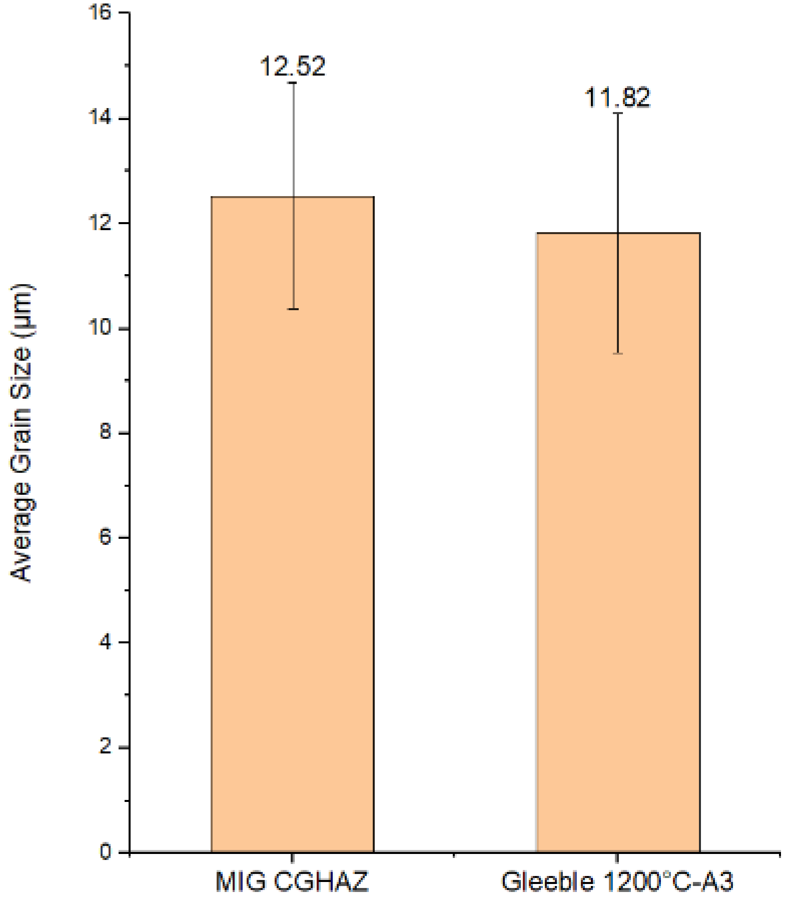
L1: 100 µm / 9 = 11.1 µm
L2: 100 µm / 5 = 20.0 µm
L3: 100 µm / 6 = 16.6 µm
L4: 100 µm / 7 = 14.28 µm
L5: 100 µm / 10 = 10 µm

Gleeble CGHAZ

Total length of segment : 100 µm

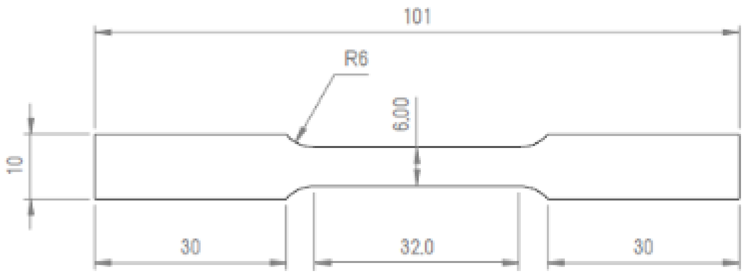


L1: 100 µm / 15 = 6.6 µm
L2: 100 µm / 8.5 = 11.7 µm
L3: 100 µm / 10.5 = 9.5 µm
L4: 100 µm / 9 = 11.1 µm
L5: 100 µm / 8.5 = 11.7 µm

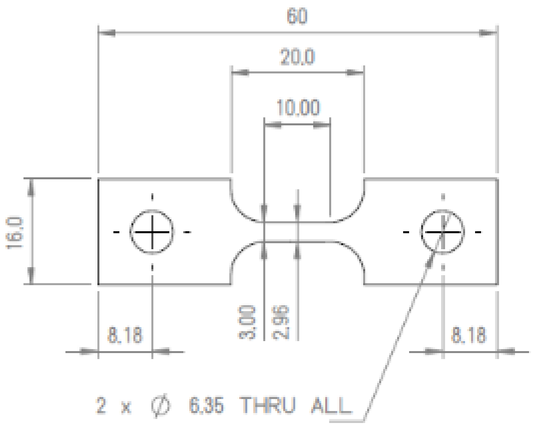


Coupon tests

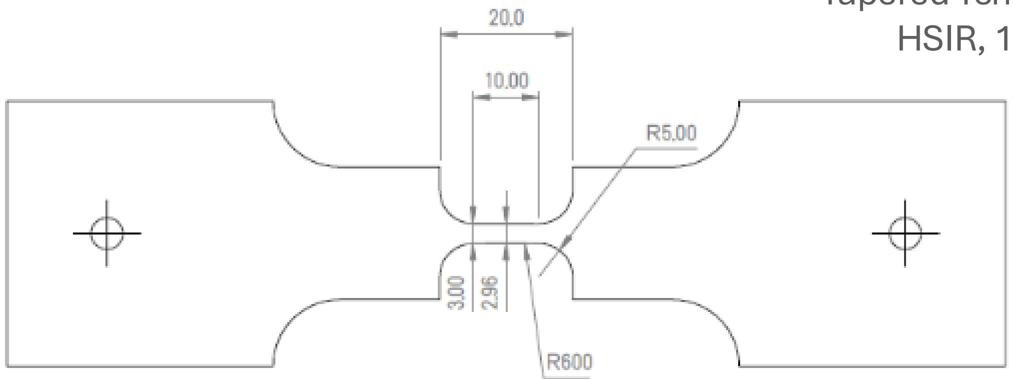
Specimen Type	Material Condition	Strain Rates [1/s]		
		0.001	1	~100
subASTM	As-Received	5		
Tapered Tensile FG	As-Received	3		
Tapered Tensile FG	Gleeble	5		
Tapered Tensile HISR	Gleeble		5	5
Notch Tensile FG	Gleeble	5		
Notch Tensile HISR	Gleeble		5	5
Hole Tension FG	Gleeble	5		



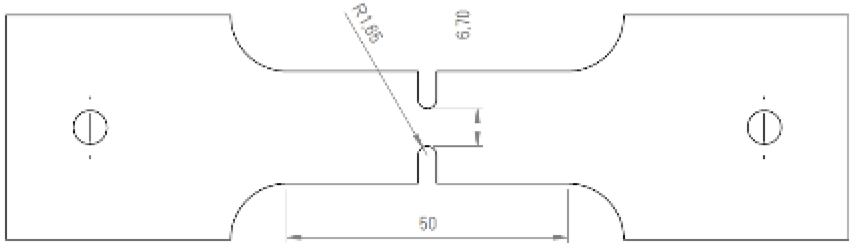
subsized ASTM E8, QS



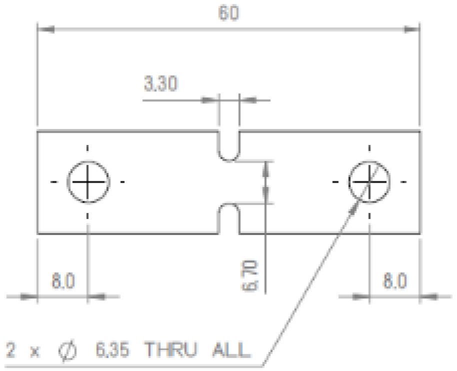
Tapered Tensile (1%) – For HSIR, 1 & 100 s^{-1}



Tapered Tensile (1%) – From Gleeble coupon, QS



Notch tensile From Gleeble coupon, QS



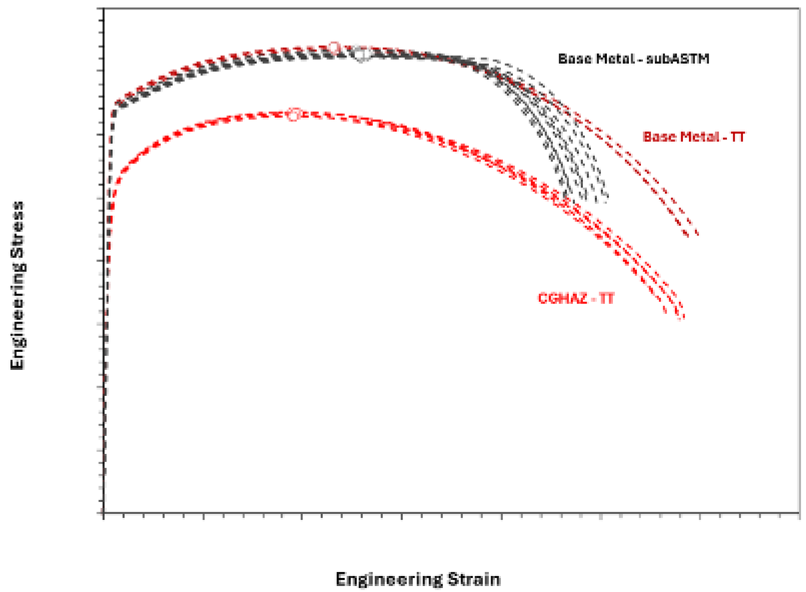
Notch tensile For HISR, 1 & 100 s^{-1}

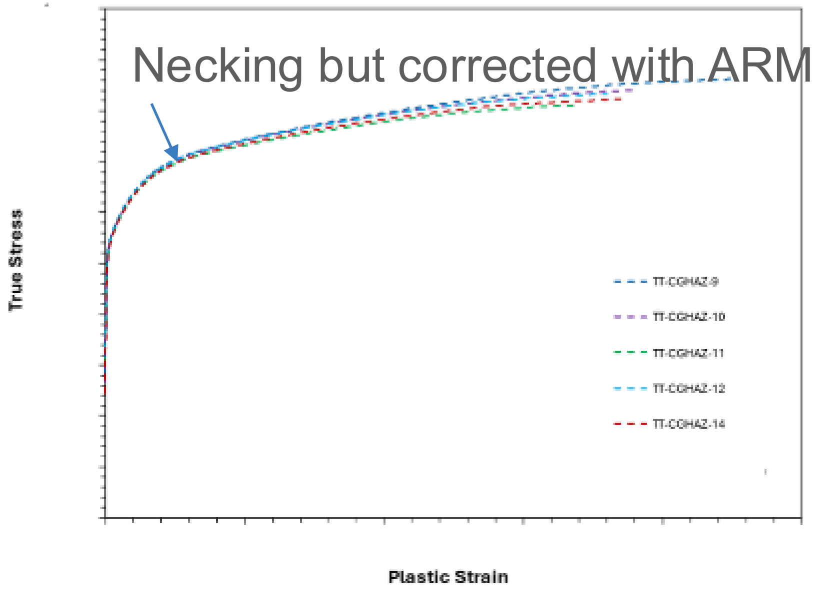
FG = From Gleeble, specimen machined directly into Gleeble coupon
HISR = Specimens machined for HISR grips (pin loaded)

Tensile properties summary

GDIS

- Excellent repeatability for all material conditions tested, overall high ductility
- Tapered Tensile (TT) shows 1% increase in hardening up to UTS and more elongation post-UTS compared to subASTM → Expected behaviour
- CGHAZ (achieved through Gleeble processing) show significant reduction in strength and mild reduction in ductility from the As-Received base metal
- Strong neck formation with significant load reduction (due to thinning) before fracture for CGHAZ
- Area analysis used to correct true stress, according to ARM (Area Reduction Method) correction





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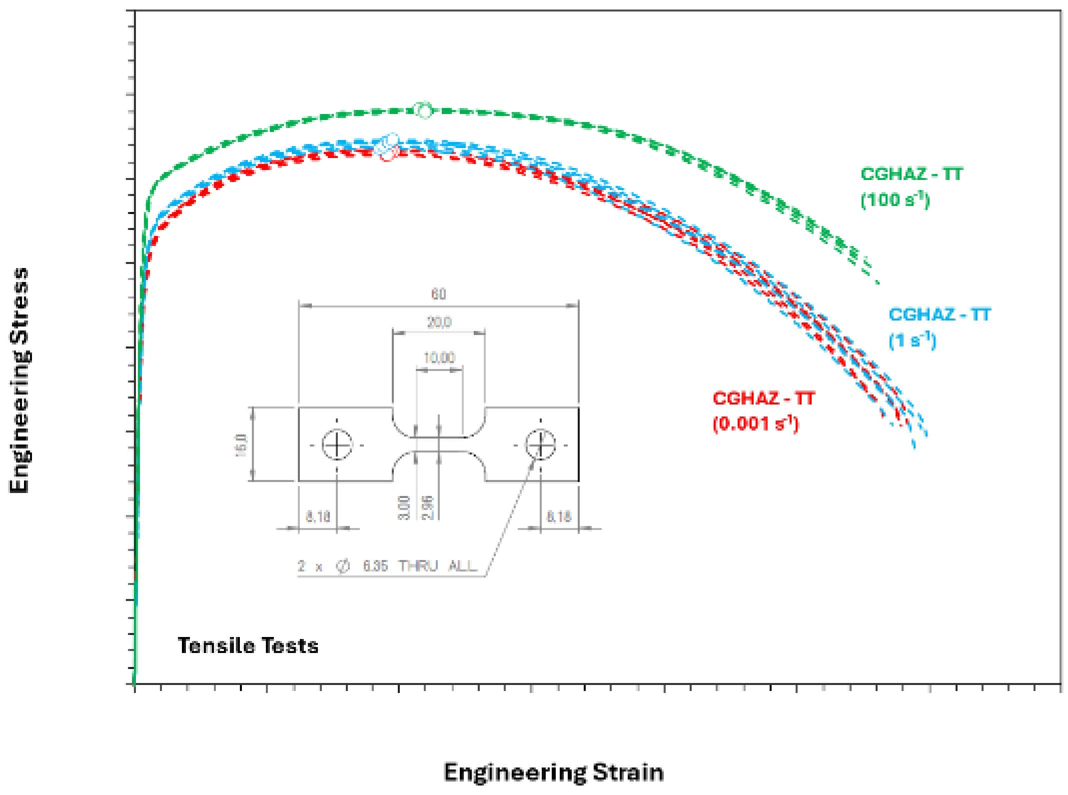
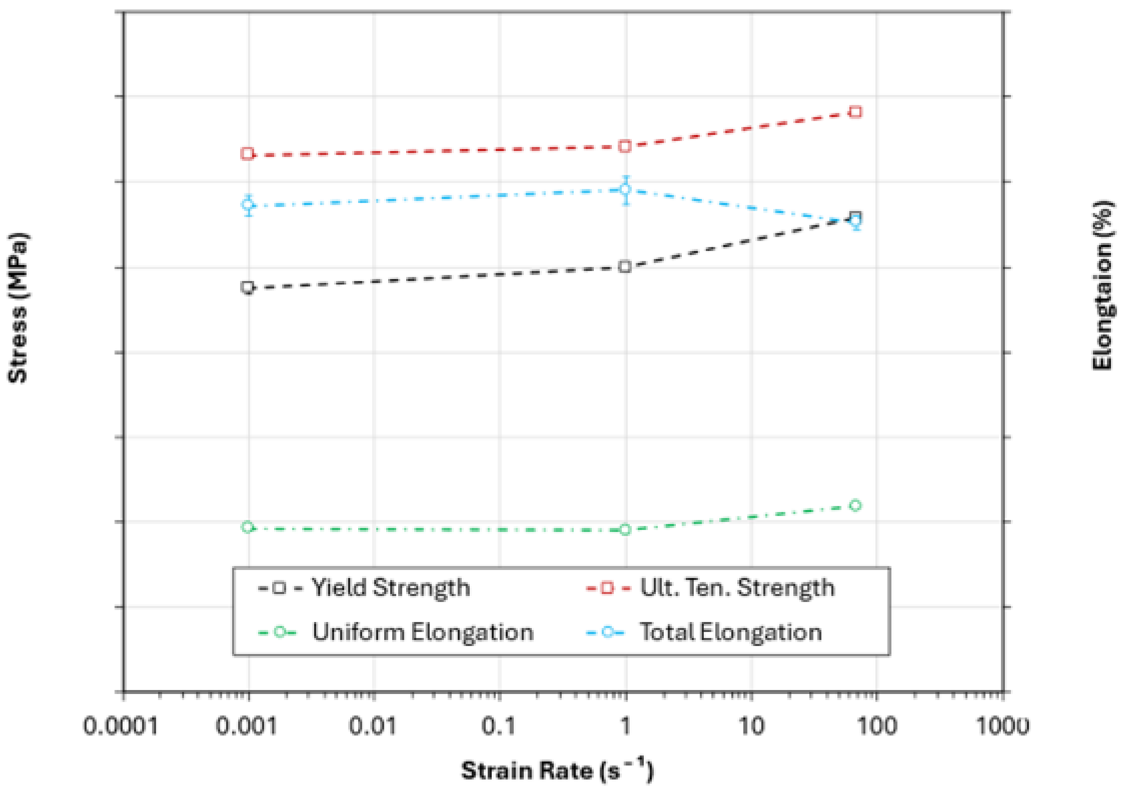
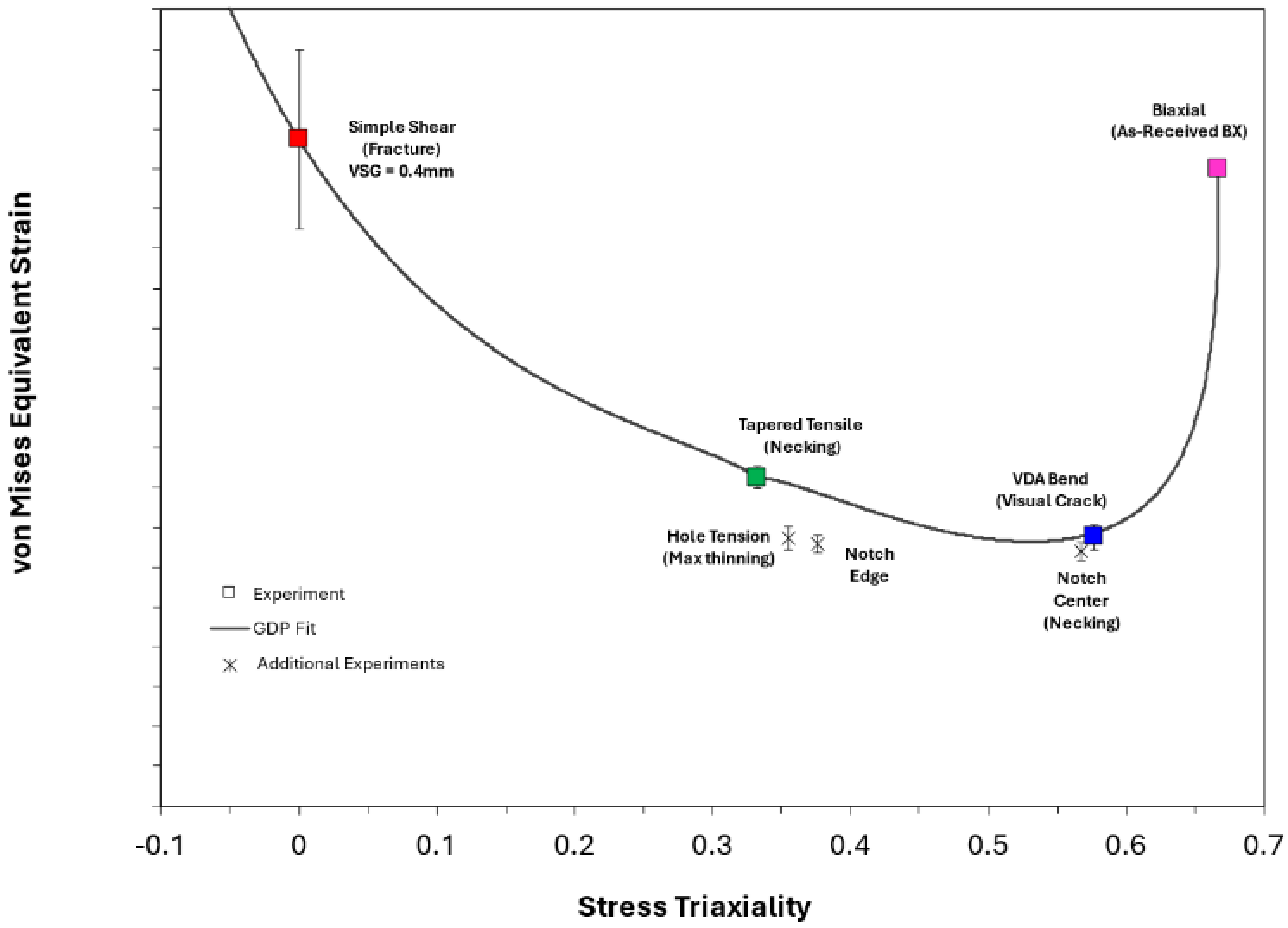
Tensile strain rate properties summary

- Tensile strength at 0.001/s and 1/s are similar but increased at 100/s significantly
- Total elongation is shorter at 100/s compared to lower strain rates





Experimental fracture locus



Conclusions

Weld sample characterization:

- Lap shear and T-Joint weld tests were performed to fracture and interrupted at 5-10% load drop
- Fracture locations were analyzed and the **Coarse-Grain HAZ (CGHAZ) was identified as fracture initiation**

Gleeble processing :

- Gleeble used to recreate time-temperature histories of plausible CGHAZ conditions
- Approximately 40mm, centered on specimen, contains uniform hardness (±5% of center)

Gleeble sample characterization:

- OM and SEM analysis confirm [T3→ Air 3 cooling] condition best recreate the real CGHAZ

Constitutive and Fracture Characterization:

- Constitutive and fracture tests performed on Gleeble processed specimens to characterize CGHAZ properties under quasi-static conditions ($0.001s^{-1}$)
  - Shear, uniaxial tensile, hole tension, notch tension, v-bend, quasi-biaxial
- Strain rates from ~0.001 to 100 s^{-1} examined for select geometries
  - Shear, uniaxial tensile, and notch tension geometries

ACKNOWLEDGEMENT

The authors gratefully acknowledge the **University of Waterloo Forming and Crash Lab** for conducting the tests and analyzing the experimental data for this project.

Cameron Tolton

Mohammad Shojaee

Jose Imbert-Boyd

Prof. Cliff Butcher

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THANK YOU FOR YOUR ATTENTION!