LME EVALUATION OF 3RD GEN. ADVANCED HIGH STRENGTH SHEET STEELS

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A/S P Auto/Steel Partnership

Joining in Car Body Engineering; 19-20 February 2020 Detroit, MI, USA

LME Research Impact

LME Testing Approach

- Strain Rate
- Heating Rate
- Hold Time
- Temperature Range

Current studies feature range of test conditions which impact LME sensitivity

LME Testing Goal

- Simplify test conditions
- Design a repeatable test to compare materials
- Simulate conditions found during RSW

Background

Strain Rate

- Strain rate can affect microstructural evolution at high temperature
- Increased strain rate reduces allowable time for stress relief
  - Promotes crack initiation
  - Fernandes and Jones work illustrates ductility drop experienced at high strain rates
- Spot welds are subjected to significant material strain

Temperature Range

- LME causes 'ductility trough', a material's specific temperature range in which it is susceptible to brittle failure
- 'Ductility trough' temperature range can vary depending on material

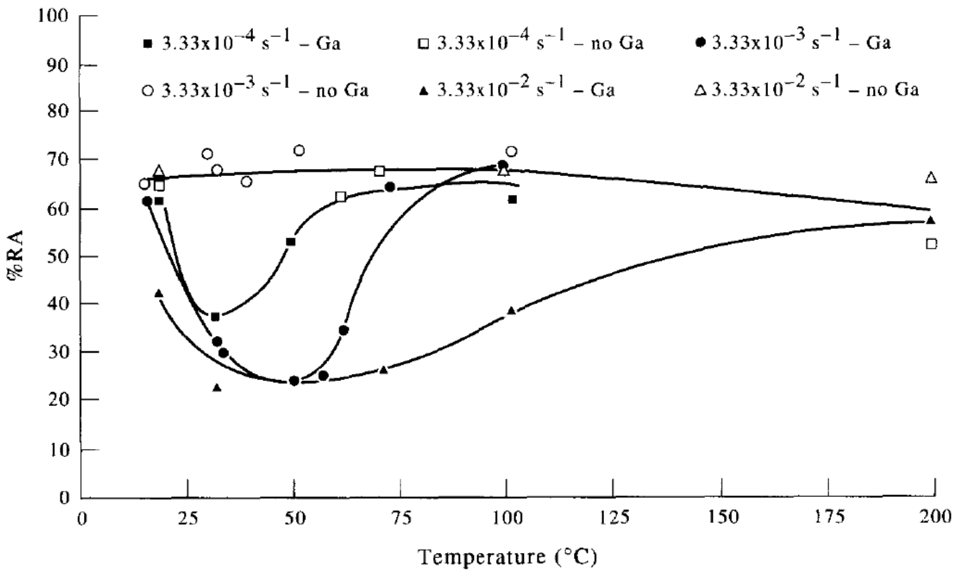
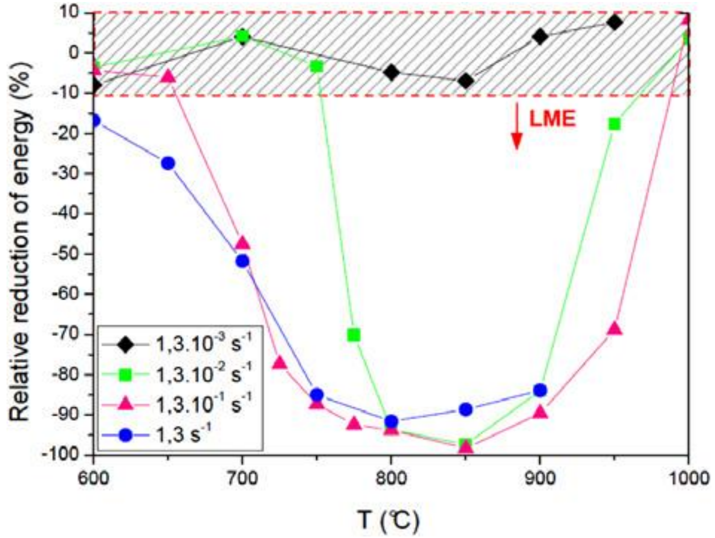


Fig. 3. Plot of %RA as a function of temperature at various initial strain rates for CZ109 brass.

P. J. Fernandes and D. R. Jones, "The effects of microstructure on crack initiation in liquid-metal environments," *Engineering Failure Analysis,* 1997.



C. Beal, X. Kleber, D. Fabregue and M. Bouzekri, "Liquid zinc embrittlement of twinning-induced plasticity steel," Scripta Materialia, vol. 66, no. 12, pp. 1030-1033, 6 2012.

Background

Heating Rate

RSW Heating Rate

- Exceeds 1000 °C/s

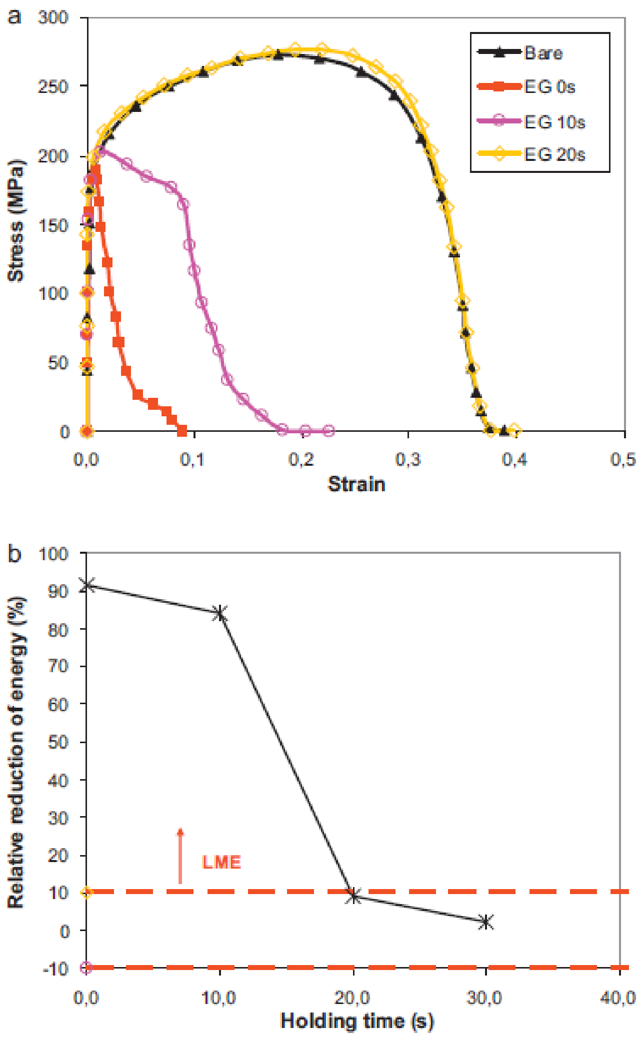
Thermo-mechanical simulation Heating Rate

- 20 °C – 100 °C/s (Jung, Beal, D. Kim)

Important to match heating rate as close as possible due to effect of hold time

Hold Time

- Shortening hold time impacts LME resistance (Bhattacharya, 2018)
- RSW experiences very short hold times, under 1 second
- Short hold time is necessary to limit sample ductility recovery



C. Beal, X. Kleber, D. Fabregue and M. Bouzekri, "Embrittlement of a zinc coated high manganese TWIP steel," *Materials Science and Engineering: A*, vol. 543, pp. 76-83, 1 5 2012.

Background

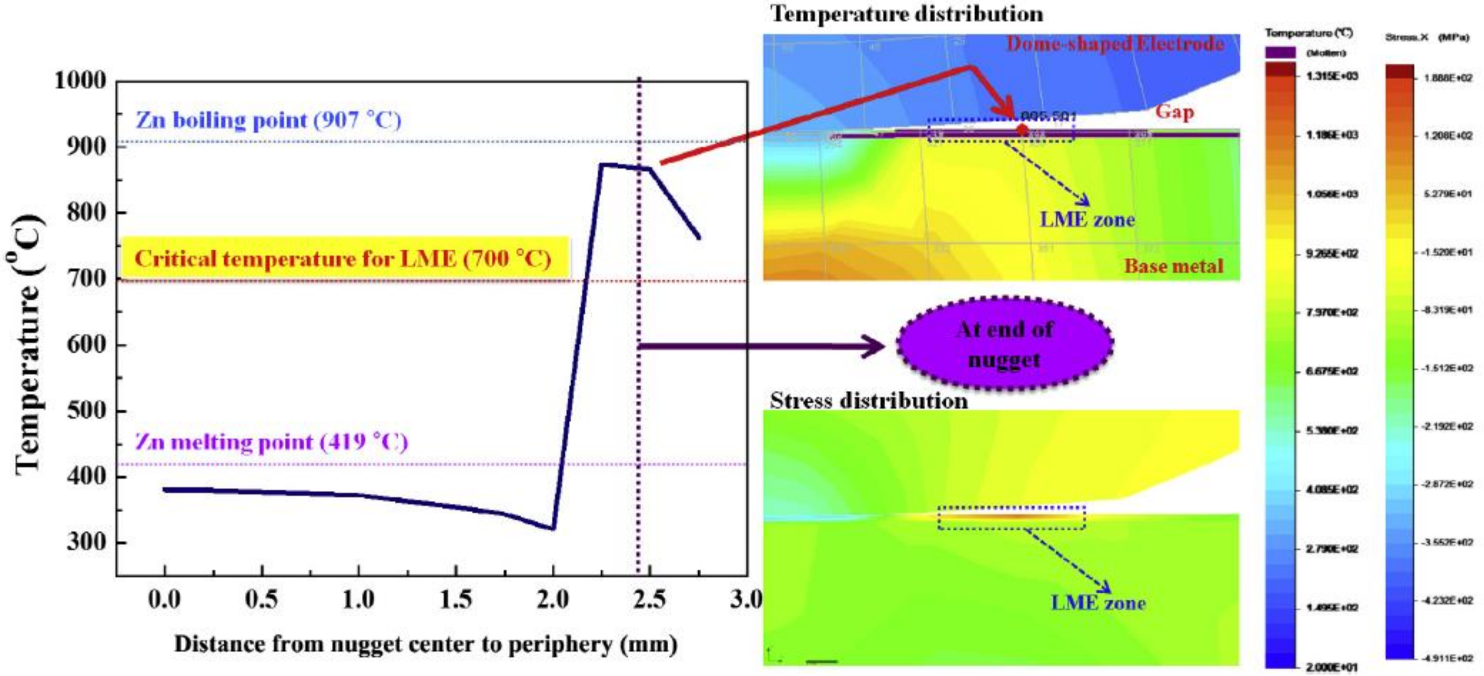
Common RSW/LME region – Weld Shoulder

- Plate/Electrode edge
  - Concentrated Stresses
  - Increased susceptibility to LME throughout this temp. range
- Zn Properties
  - Melt – 420˚C
  - Vaporization – 907˚C

Microstructure at High Temperature

- Phase transformations
  - Ferrite
  - Austenite

LME Testing designed to simulate thermo-mechanical forces experienced throughout RSW weld shoulder



R. Ashiri, M. A. Haque, C. W. Ji, M. Shamanian, H. R. Salimijazi and Y. D. Park, "Supercritical area and critical nugget diameter for liquid metal embrittlement of Zn-coated twining induced plasticity steels," Scripta Materialia, vol. 109, pp. 6-10, 1 12 2015.

Material Selection

Material	
Sample Description	Letter Reference
CR340Y410T-HSLA-EG	A
CR340Y590T-DP-HDG	B
CR450Y780T-TR-GI	C
CR700Y980T-MP-LCE-EG	D
CR600Y980T-RA-HE-GI	F
CR850Y1180T-RA-SE-GI	G
CR1200Y1500T-MS-EG	H

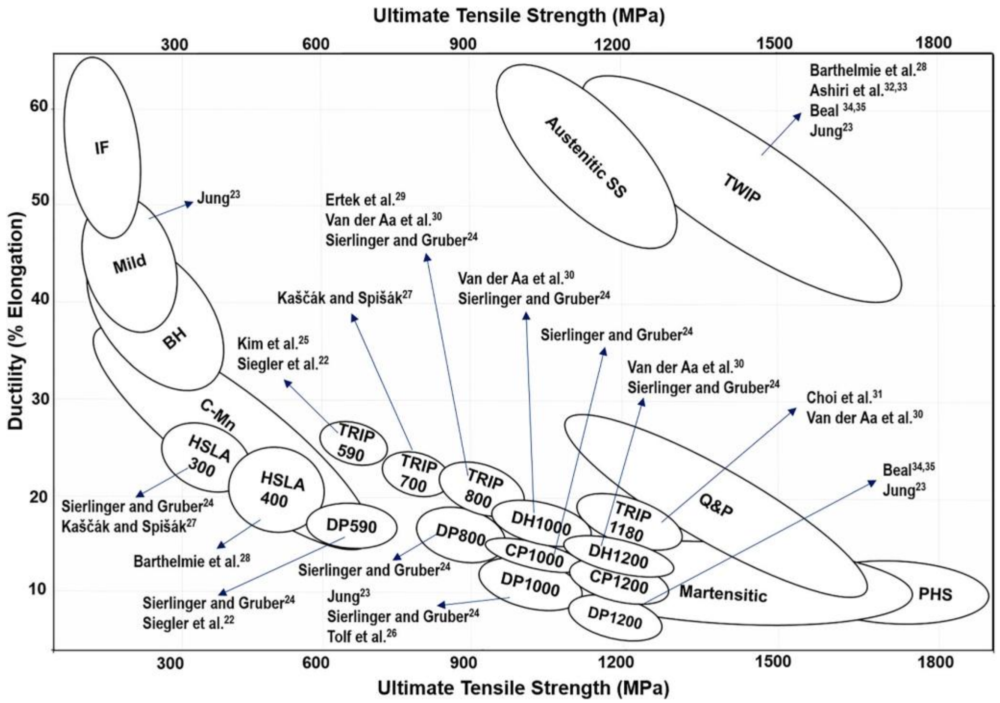
MM-XXXYZZZT-AA - Coating Type/Coating Weight

- •MM – HR or CR for substrate
- •XXX – Yield Strength Minimum (MPa)
- •ZZZ – Tensile Strength Minimum (MPa)
- •AA – Material Type
  - DP – Dual Phase
  - RA – Retained Austenite
  - CP –Complex Phase
  - TR – TRIP
  - HSLA – High Strength Low Alloy

Coating Type/Coating Weight

GI - Extragal or Ultragal
GA - Galvannealed
EG - Electrogalvanized

HDG - Hot Dipped Galvanized



D. Bhattacharya, *Liquid metal embrittlement during resistance spot welding of Zn-coated high-strength steels*, vol. 34, Taylor and Francis Ltd., 2018, pp. 1809-1829.

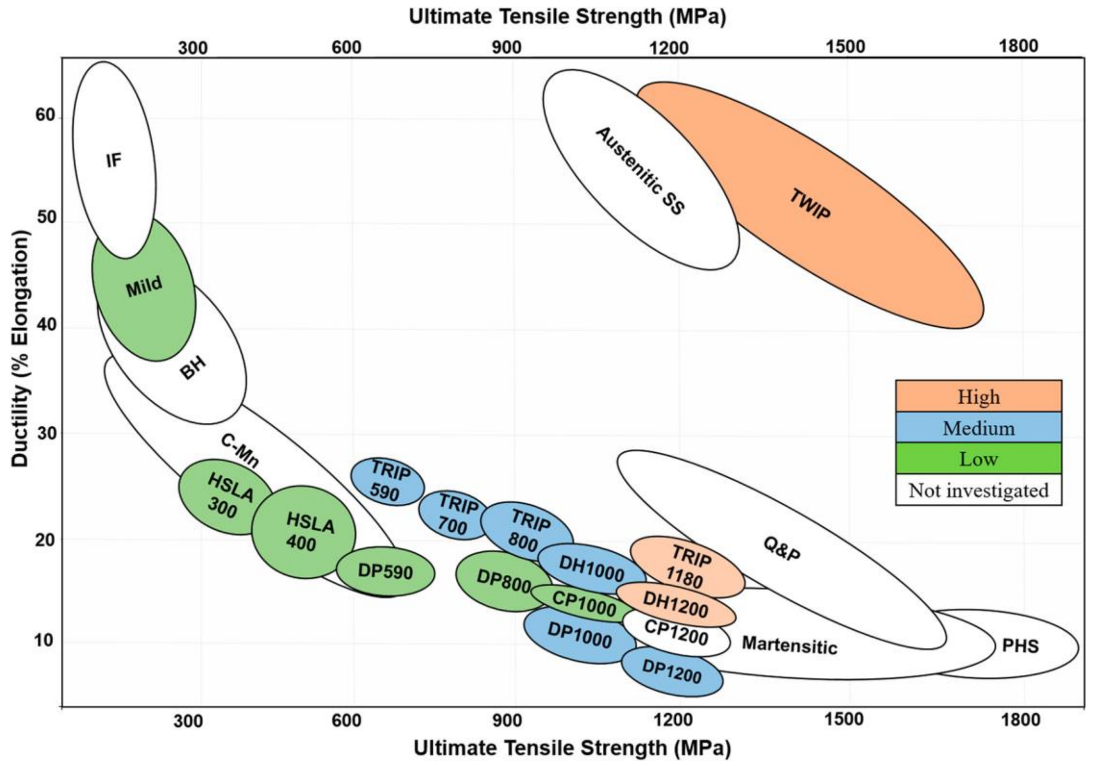
Previous AHSS LME Research

Limited Previous work on various AHSS Microstructures

- Complex Phase (CP)/Multi-Phase (MP) Microstructures
- Dual Phase (DP)
- Transformation Induced Plasticity (TRIP)
- Retained Austenite (RA)

Research Focus

- B - DP 590
- C - TRIP 780
- F - RA 980 (Q&P)

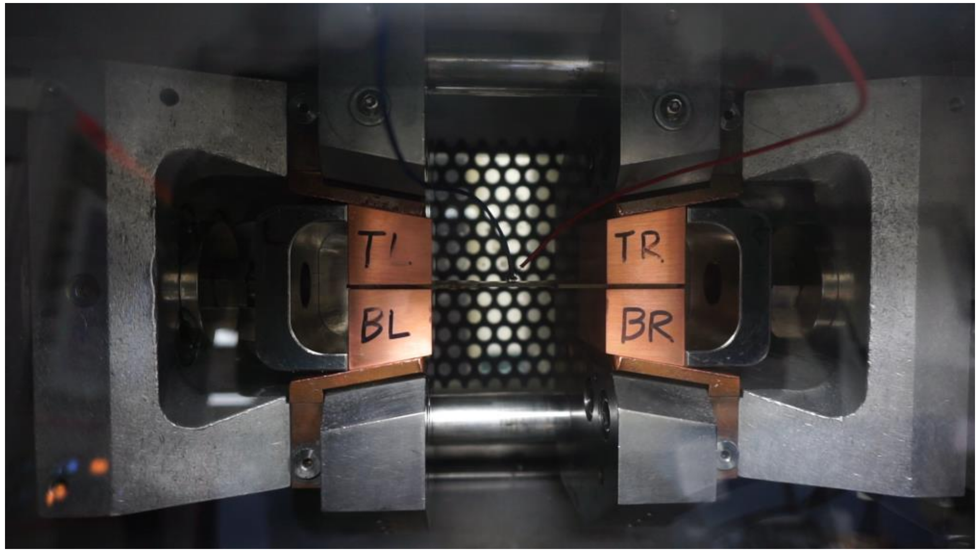


D. Bhattacharya, *Liquid metal embrittlement during resistance spot welding of Zn-coated high-strength steels,* vol. 34, Taylor and Francis Ltd., 2018, pp. 1809-1829.

Experimental Design

Simulation of Resistance Spot Welding Thermal History in Gleeble

- Sample Geometry
- Gleeble Selection/Parameters
  - Displacement Control/ Strain Rate
  - Temperature Range
  - Heating Rate
  - Hold Time
- Test Criteria
  - Qualitative
  - Quantitative
    - Max Force
    - Area Under the Curve
    - Displacement at 50% Max Force



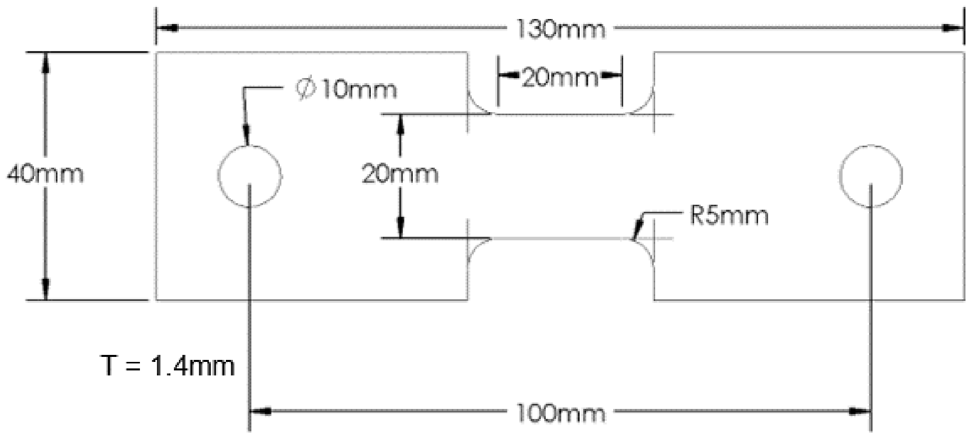
Sample Geometry

Design Criteria

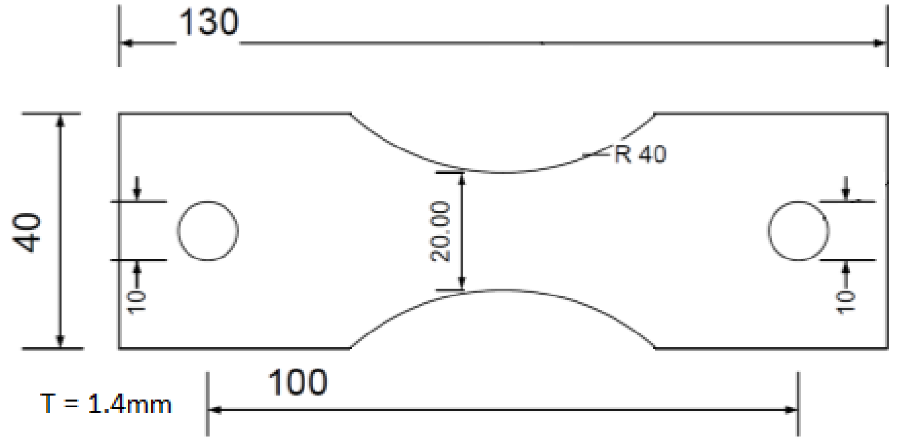
- Accurately simulate heating/strain expected in typical spot welds
- Maintain uniform temperature gradient throughout gauge length

Design Selection

- Two designs were considered – ‘U’ and ‘N’
  - ‘U’ – Uniform Gauge Length
  - ‘N’ – Notch Sample
- Design ‘U’ selected for consistent temperature throughout coupon center



‘U’ Sample

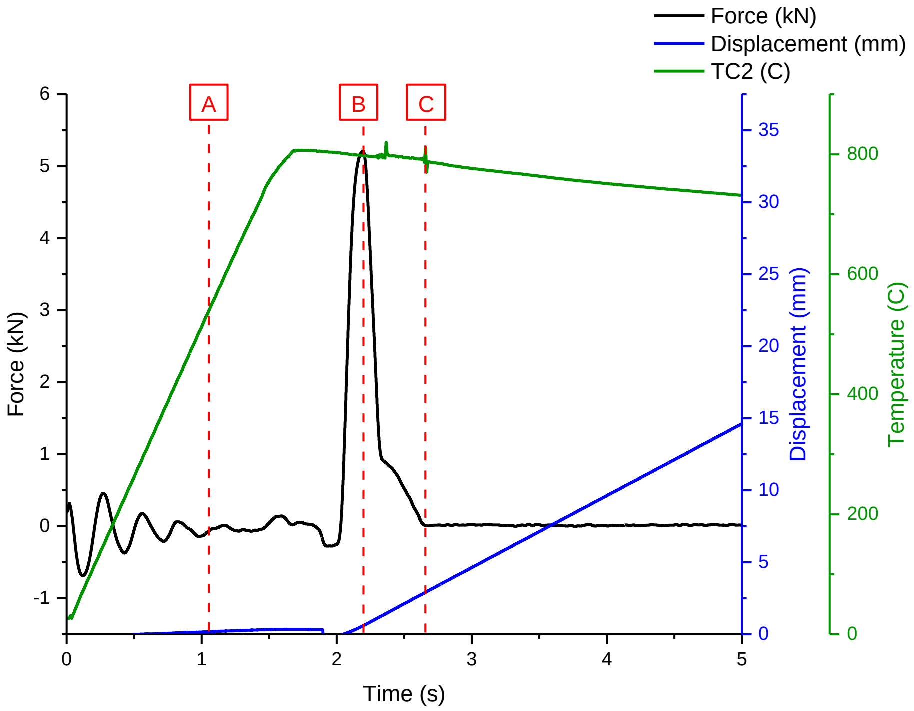


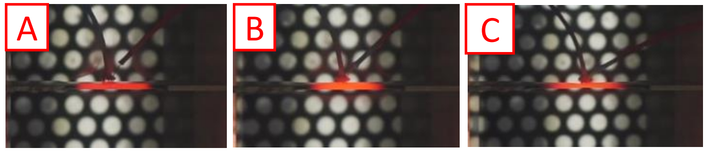
‘N’ Sample

Gleeble Test Design

Gleeble 3800-GTC

- Gleeble offers precise Thermo-mechanical control
  - Critical for displacement and force results
- Replicates heating/forces experienced during RSW
- Excellent parameter control
  - Head rate
    - 5, 50, 500 mm/s
  - Heating rate
    - 500°C/s
  - Temperature Range
    - 400°C - 800°C
- Argon-backed environment





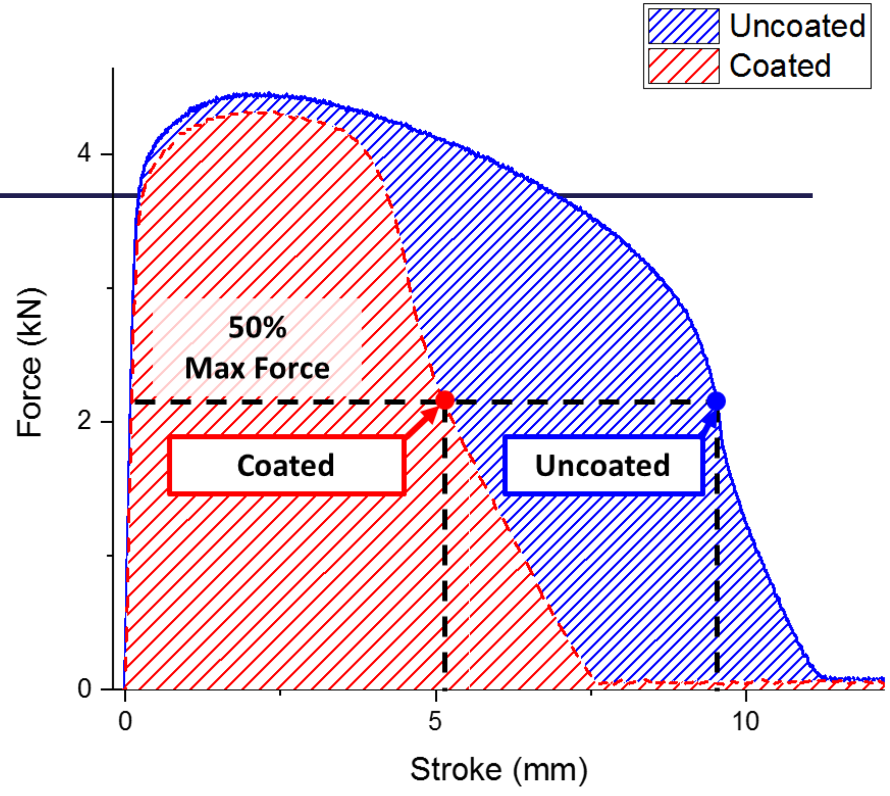
Test Criteria

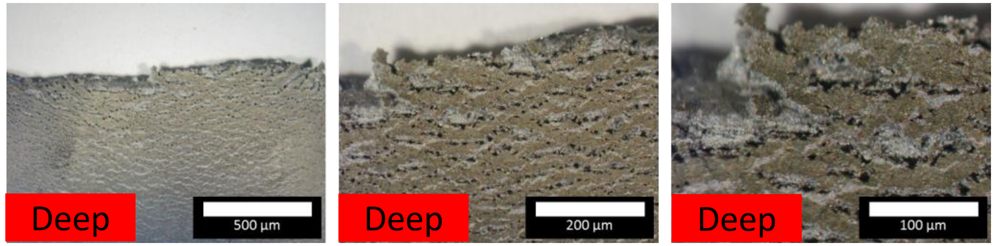
Quantitative

- Data Collected
  - Area under the curve
  - Max force
  - Stroke at 50% Max Force
- Efficiency factors determined through comparison of coated vs. uncoated data

Qualitative

- Visual inspection confirms LME and its severity
- Assigned efficiency value
  - Deep, Shallow, Threshold, No LME





Color Legend:	Efficiency Factor
Deep LME	Efficiency Factor<75%
Shallow LME	75%<=Efficiency Factor<85%
Threshold	85%<=Efficiency Factor<92.5%
No LME	Efficiency Factor>=92.5%

Qualitative Visual Guide

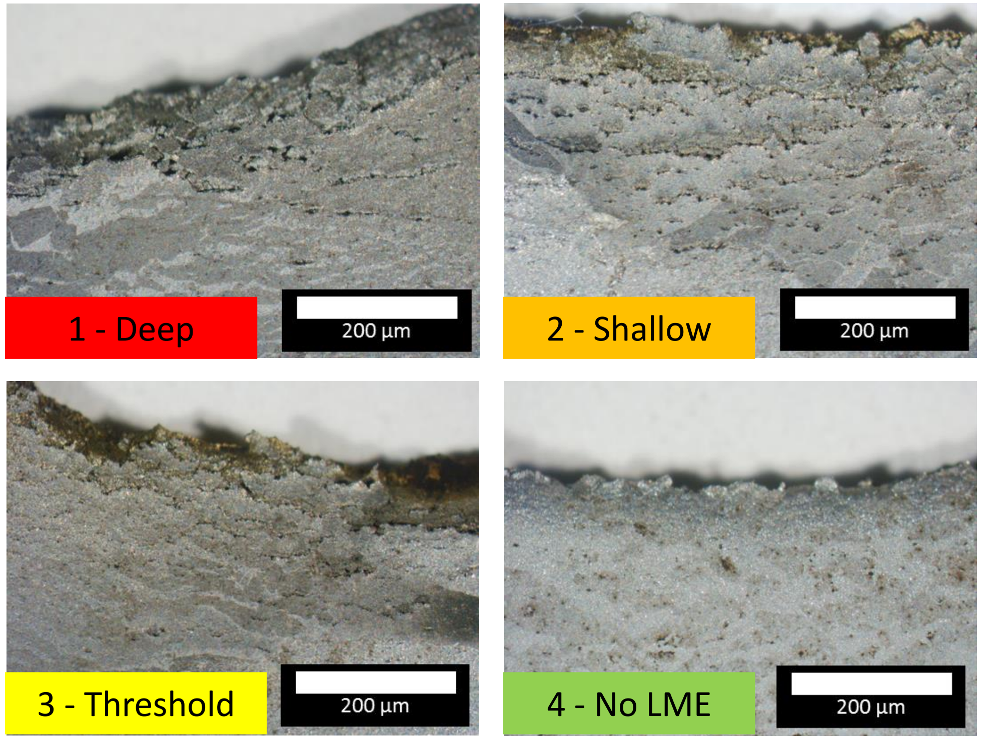
1) Deep
- Cracks clearly seen by the naked eye penetrated the thickness of test sample

2) Shallow
- Observed by naked eye
- Did not penetrate through entire thickness of test sample

3) Threshold
- Observed by illuminated magnifier
- Cracking concentrated near fracture surface

4) No LME
- No cracking observed under illuminated magnifier

	Color Legend:	Efficiency Factor
1	Deep LME	Efficiency Factor<75%
2	Shallow LME	75%<=Efficiency Factor<85%
3	Threshold	85%<=Efficiency Factor<92.5%
4	No LME	Efficiency Factor>=92.5%



		Temperature (°C)																
		400	425	450	475	500	525	550	575	600	625	650	675	700	725	750	775	800
Head Rate (mm/s)	500																	
	50							4				3	2		1			
	5																	

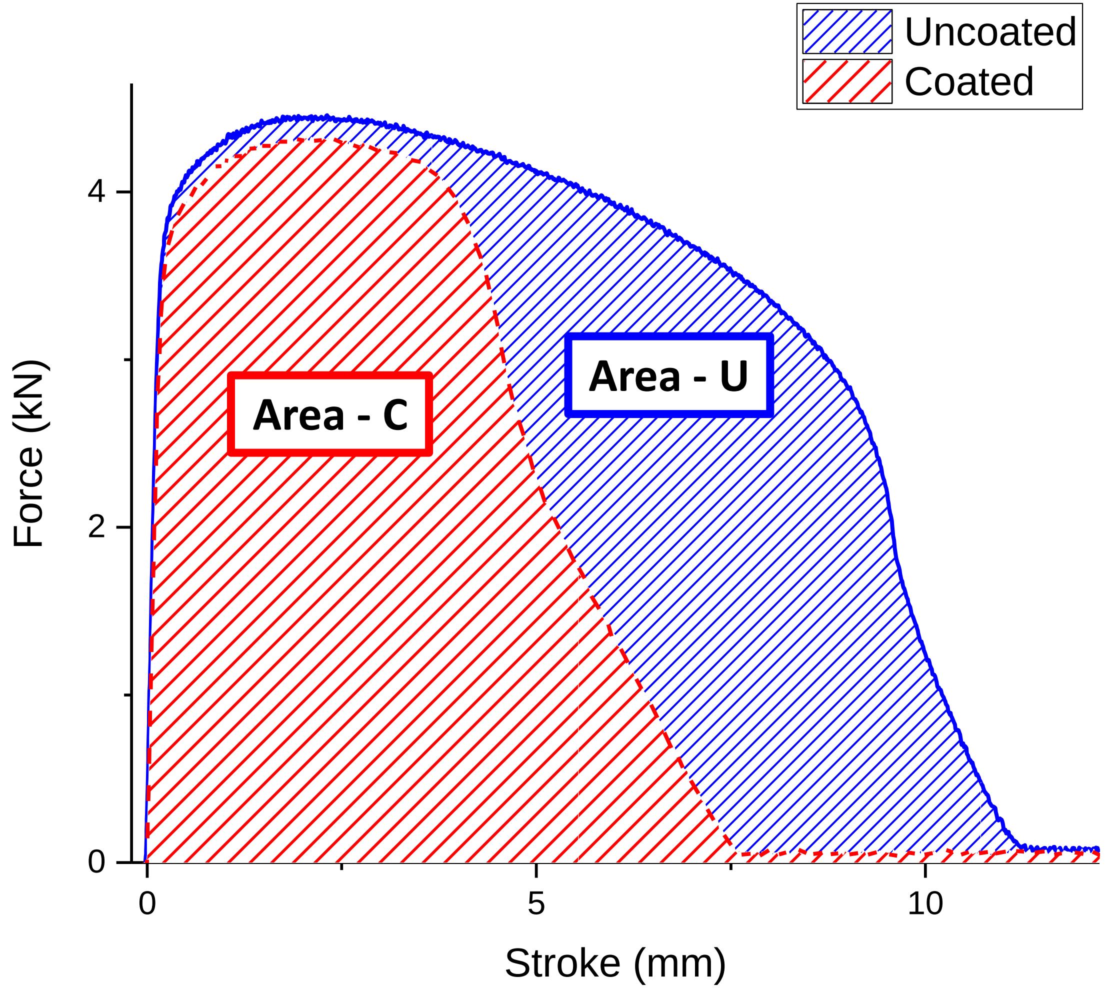
Area Under the Curve

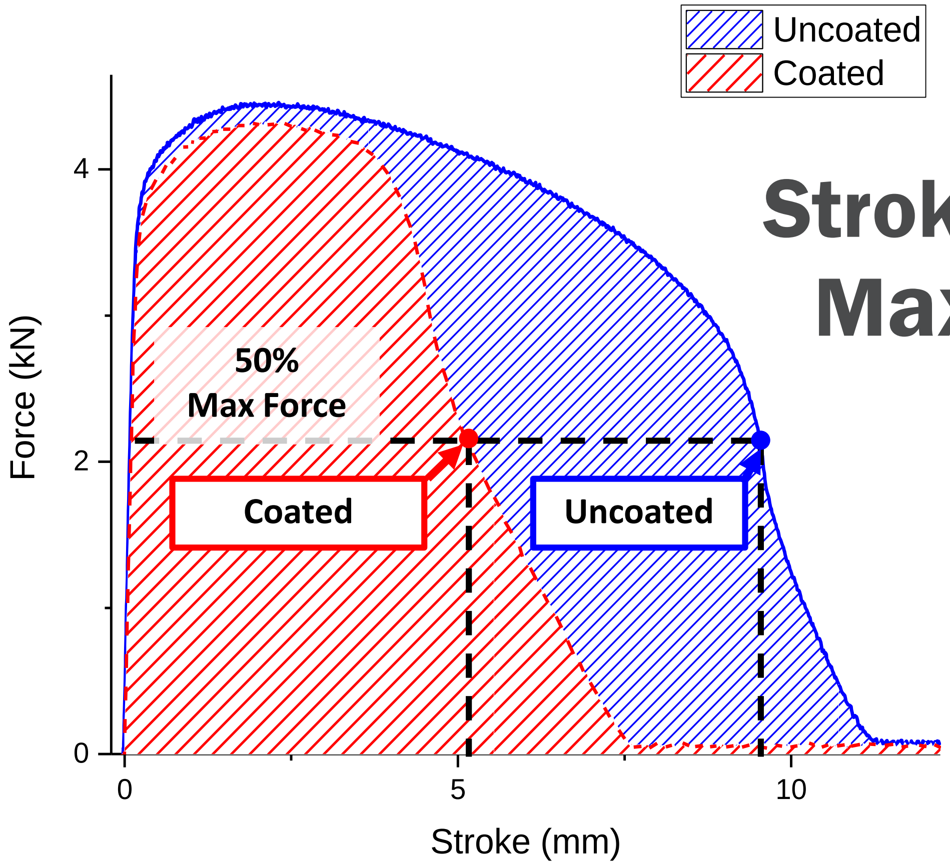
- Coated Sample Area Under the Curve: C
- Uncoated Sample Area Under the Curve: U
- Delta Area Under the Curve:

$$\Delta A = \frac{C-U}{U}$$

- Efficiency Factor: E%

$$E\% = (C / U) \times 100$$





Stroke at 50% Max Force

- Coated Sample Stroke at 50% of the Max Force: C
- Uncoated Sample Stroke at 50% of the Max Force: U
- Delta Stroke at 50% of the Max Force: ΔD

$$\Delta D = \frac{C-U}{U}$$

- Efficiency Factor: E%

$$E\% = (C / U) \times 100$$

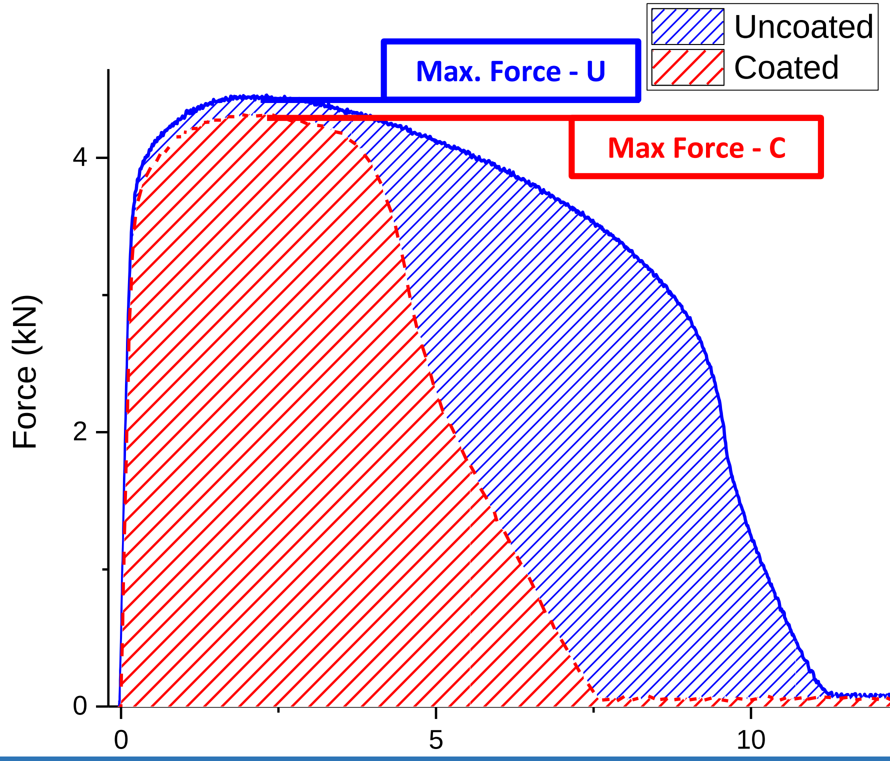
Max Force

- Coated Sample Max Force: C
- Uncoated Sample Max Force: U
- Delta Max Force: ΔD

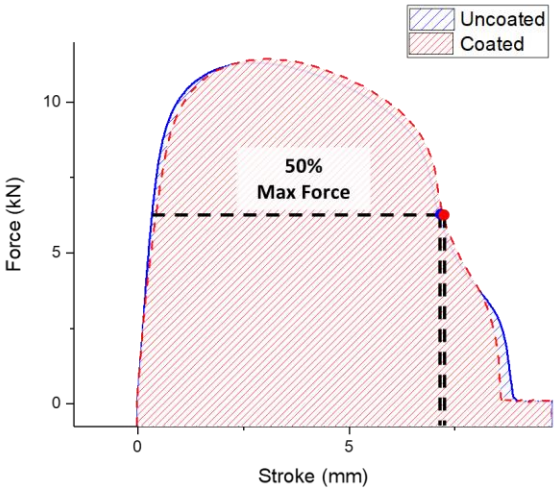
$$\Delta D = \frac{C-U}{U}$$

- Efficiency Factor: E%

$$E\% = (C / U) \times 100$$



Quantitative and Qualitative Comparison of LME Characterization



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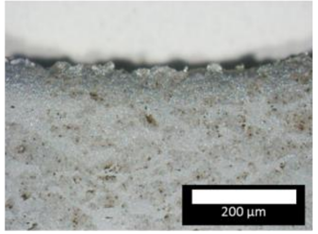

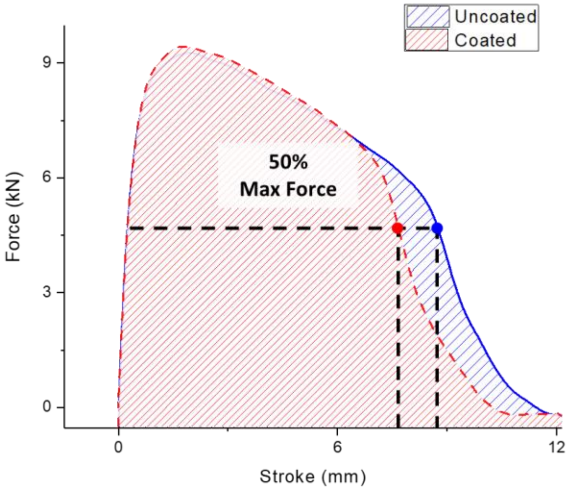

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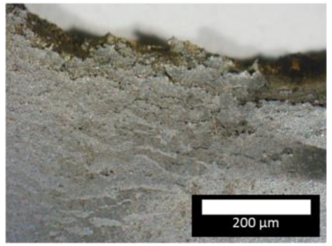

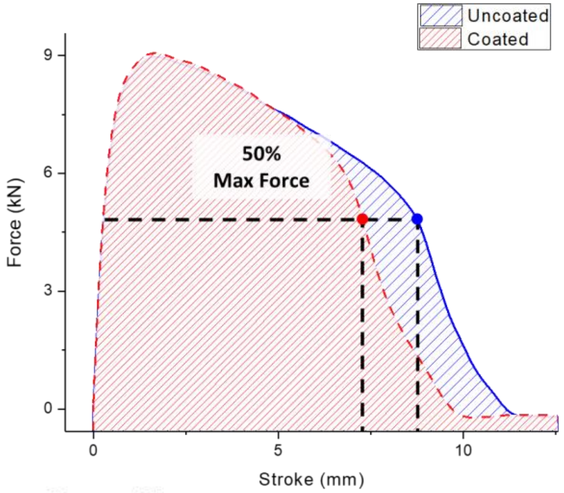

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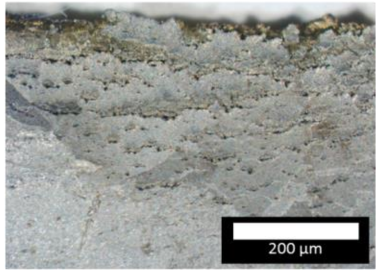

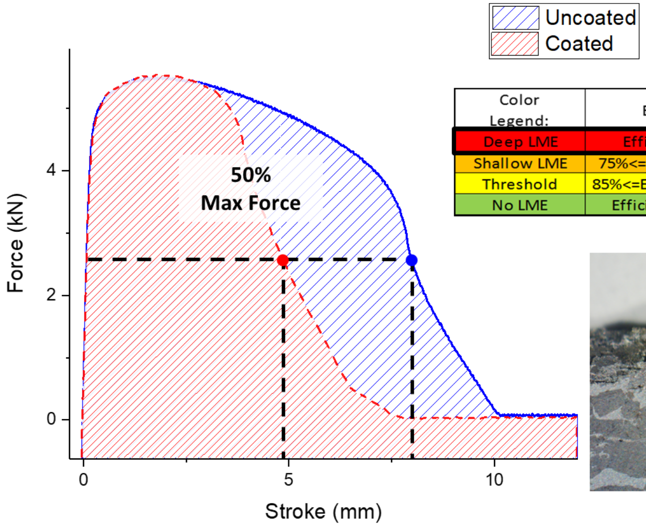

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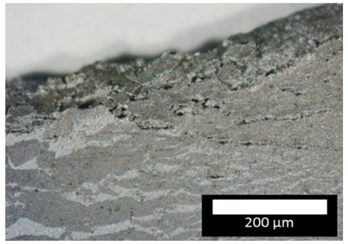

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Threshold	85%<=Efficiency Factor<92.5%
No LME	Efficiency Factor>=92.5%

Data Validation – Green Line

Qualitative vs. Quantitative Results

DP Material

Qualitative

		Temperature (°C)																
		400	425	450	475	500	525	550	575	600	625	650	675	700	725	750	775	800
Head Rate (mm/s)	500																	
	50																	
	5																	

Quantitative

		Temperature (°C)																
		400	425	450	475	500	525	550	575	600	625	650	675	700	725	750	775	800
Head Rate (mm/s)	500																	
	50																	
	5																	

TRIP Material

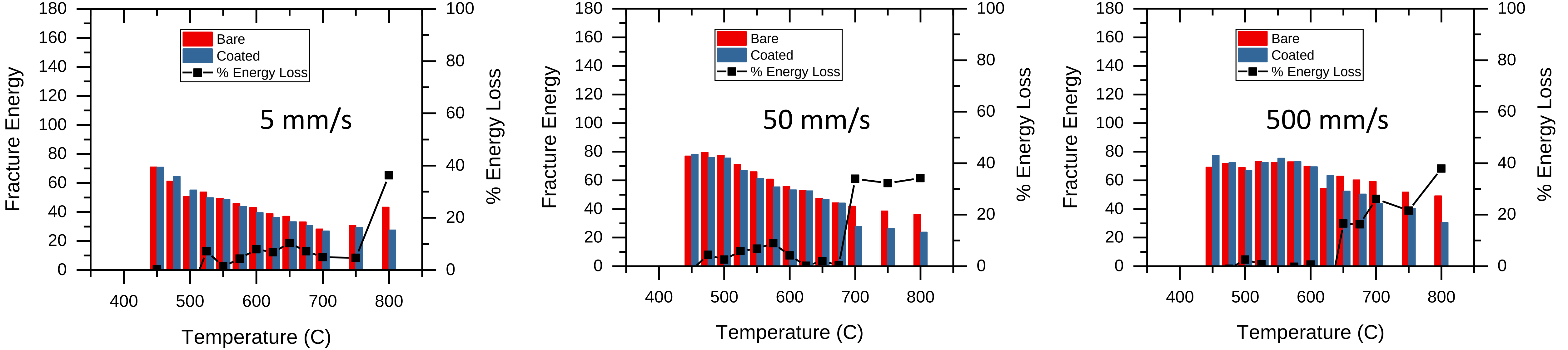
Qualitative

		Temperature (°C)																
		400	425	450	475	500	525	550	575	600	625	650	675	700	725	750	775	800
Head Rate (mm/s)	500																	
	50																	
	5																	

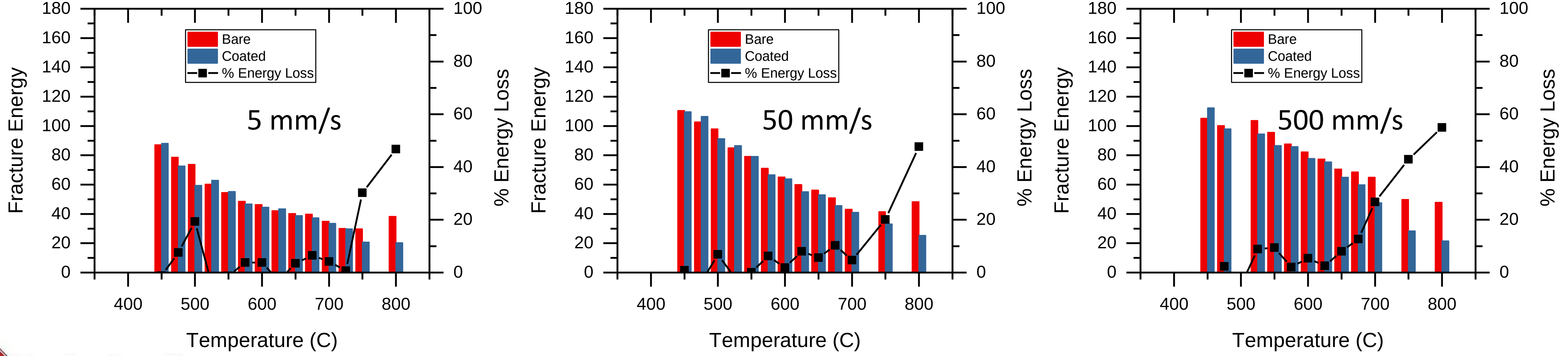
Quantitative

		Temperature (°C)																
		400	425	450	475	500	525	550	575	600	625	650	675	700	725	750	775	800
Head Rate (mm/s)	500																	
	50																	
	5																	

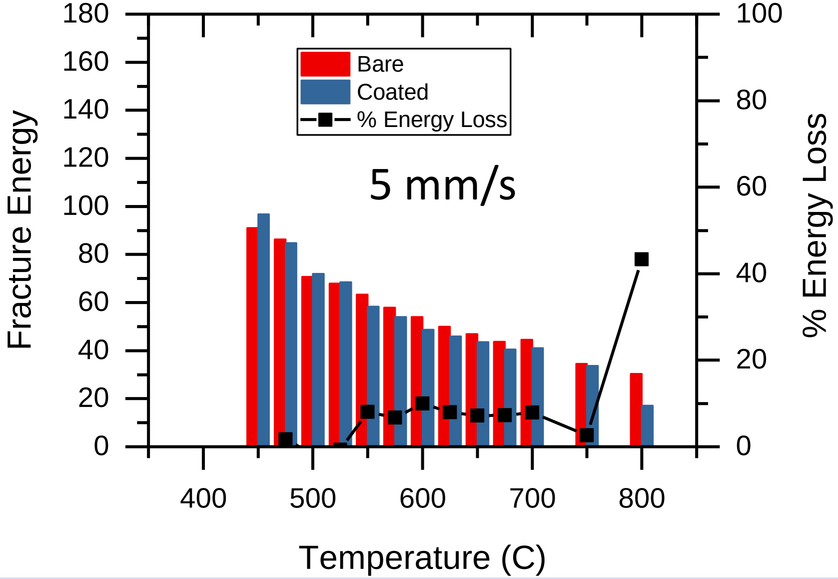
% Energy Loss – HSLA

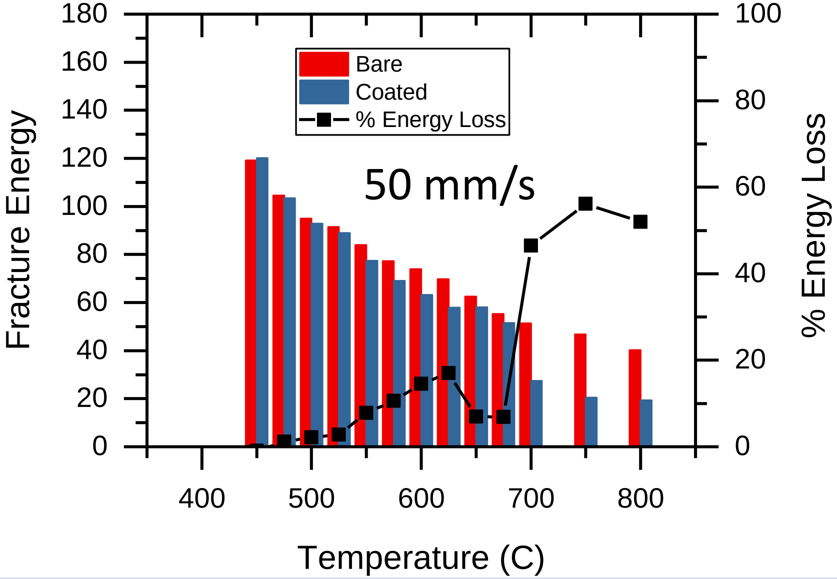


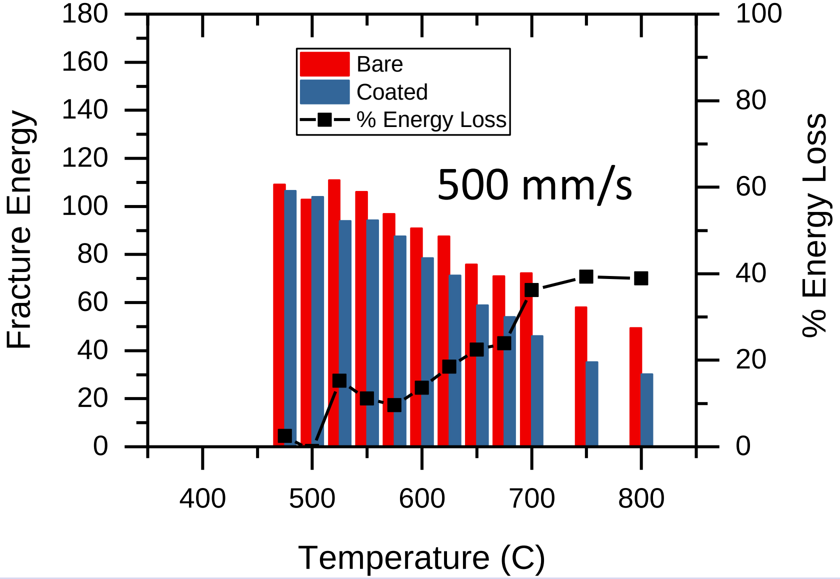
% Energy Loss – DP



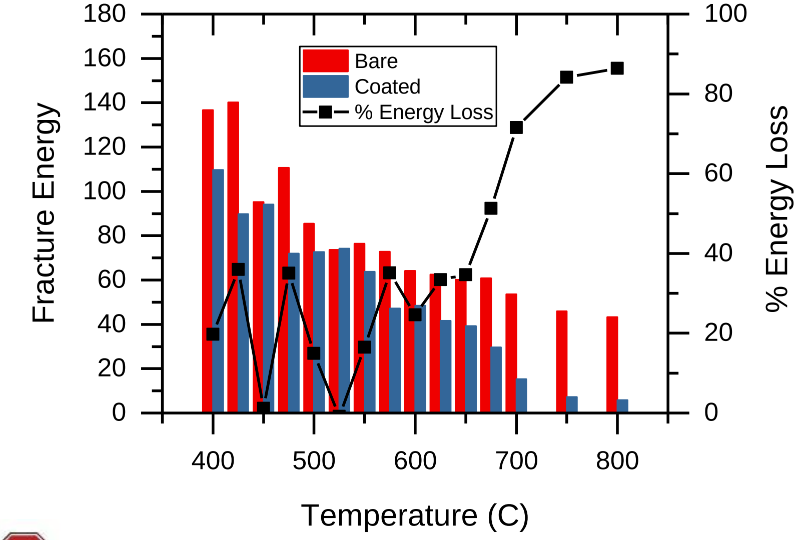
% Energy Loss – TRIP

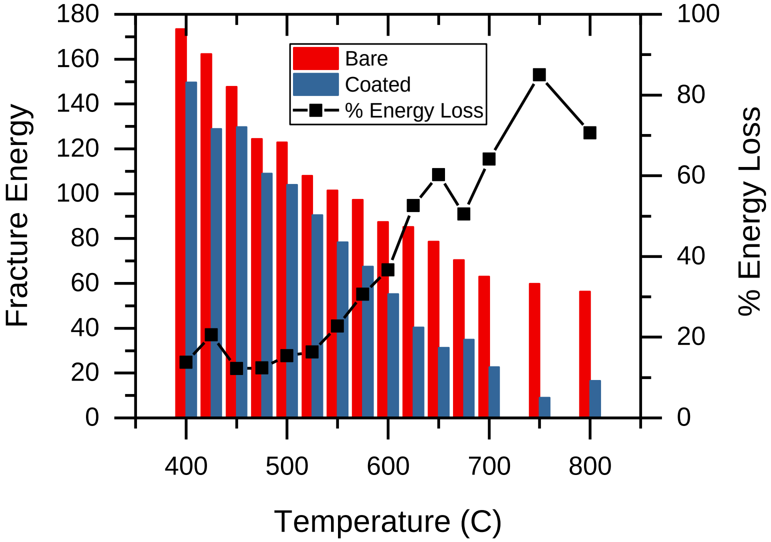


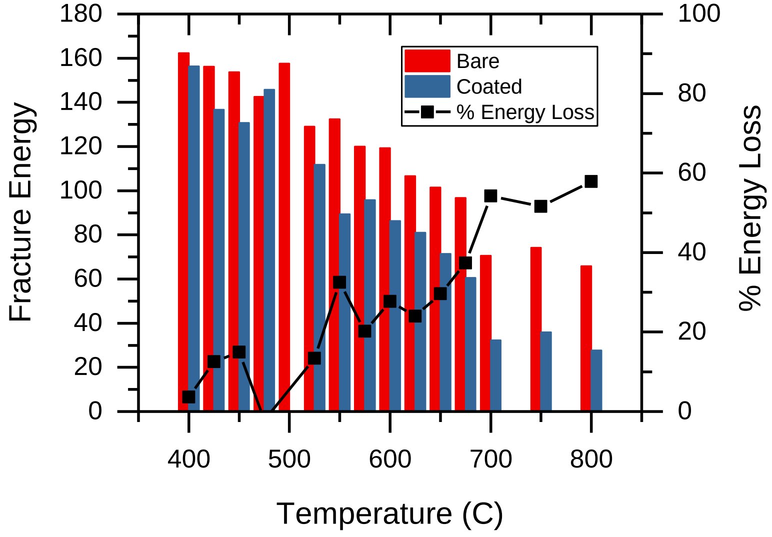




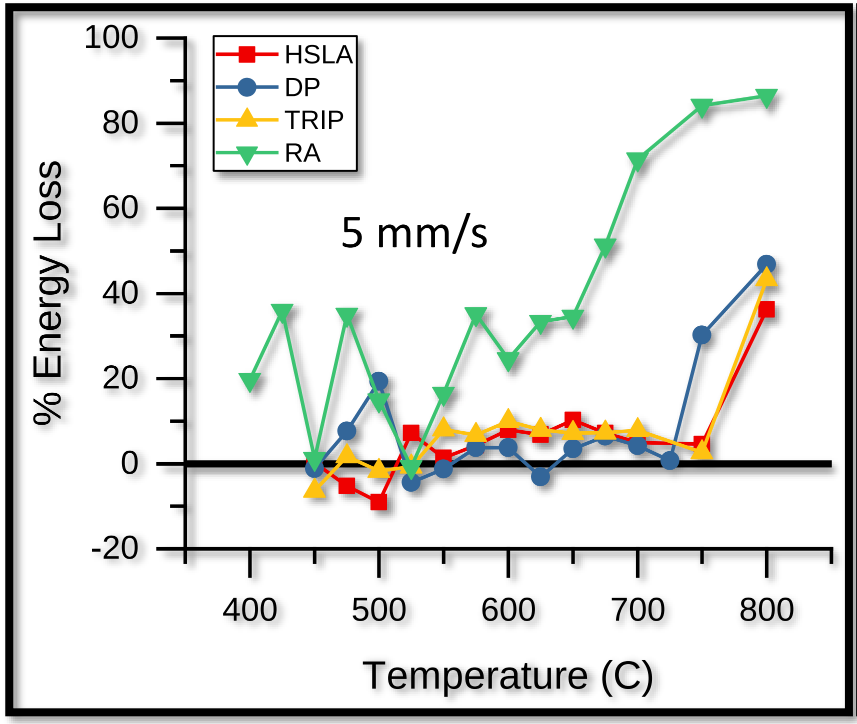
% Energy Loss – RA

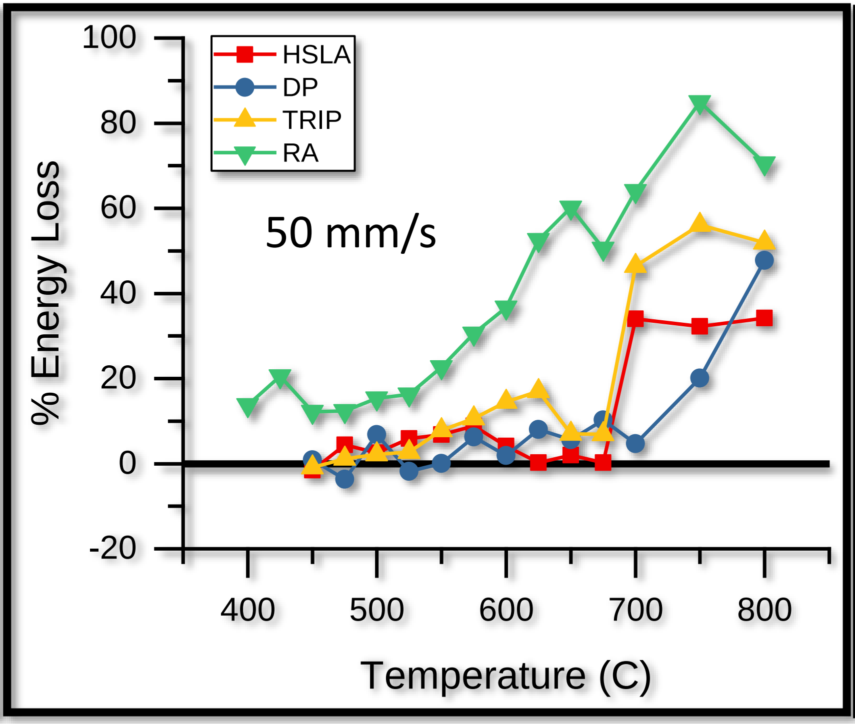


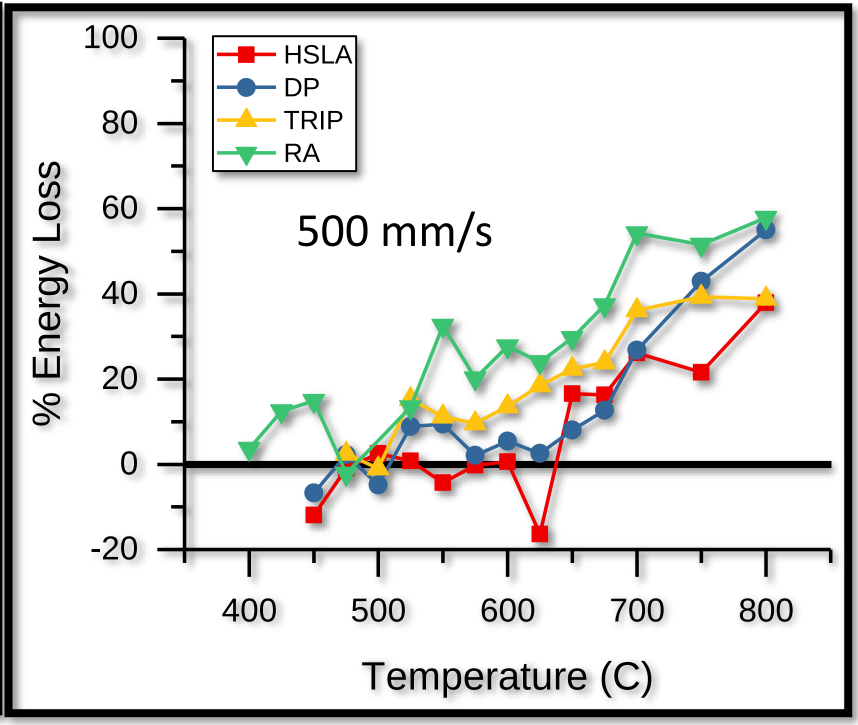




Strain Rate Effect on Ductility Lost







Conclusions

Gleeble Test Procedure

- Rapid heating and stroke rate
  - Provide accurate simulation of RSW
  - Indication of LME start temperature

Materials & Displacement rate

- Quantitative & Qualitative Observations
  - Good consistency between quantitative and qualitative observations.
  - DP – Low LME susceptibility.
  - TRIP – Moderate LME susceptibility.
  - Energy Loss Graphs indicate RA steels feature increased LME susceptibility.
  - LME start temperature decreases from DP to TRIP and RA steel.
  - Displacement rate (or strain rate) decreases LME.

LME Legend

Color Legend:	Efficiency Factor
Deep LME	Efficiency Factor<75%
Shallow LME	75%<=Efficiency Factor<85%
Threshold	85%<=Efficiency Factor<92.5%
No LME	Efficiency Factor>=92.5%

DP – Material B

		Temperature (°C)																
		400	425	450	475	500	525	550	575	600	625	650	675	700	725	750	775	800
Head Rate (mm/s)	500			Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Orange	Red		Red		Red
	50			Green	Green	Green	Green	Green	Green	Green	Green	Yellow	Orange	Orange	Red	Red		Red
	5			Green	Green	Green	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Red		Red

TRIP – Material C

		Temperature (°C)																
		400	425	450	475	500	525	550	575	600	625	650	675	700	725	750	775	800
Head Rate (mm/s)	500		Green	Green	Green	Green	Yellow	Yellow	Orange	Orange	Red	Red	Red	Red		Red		Red
	50	Green	Green	Green	Green	Green	Green	Yellow	Yellow	Yellow	Yellow	Yellow	Orange	Red		Red		Red
	5	Green	Green	Green	Green	Green	Green	Green	Green	Green	Yellow	Green	Green	Yellow	Orange	Red		Red

RA – Material F

		Temperature (°C)																
		400	425	450	475	500	525	550	575	600	625	650	675	700	725	750	775	800
Head Rate (mm/s)	500	Green	Yellow	Yellow	Yellow	Yellow	Orange	Red	Orange	Red	Red	Red	Red	Red		Red		Red
	50	Green	Yellow	Yellow	Yellow	Orange	Red	Red	Red	Red	Red	Red	Red	Red		Red		Red
	5	Green	Yellow	Yellow	Yellow	Red	Red	Red	Red	Red	Red	Red	Red	Red		Red		Red

Acknowledgements

- We would like to thank Dr. Michael Karagoulis for his significant contributions throughout this work. As well as Auto/Steel Partnership (ASP) and Eric McCarty the project manager of ASP Joining Team, for their constant support throughout the project.