ZCO-73: Forming and Joining of 3G and Hot Press Formed Steels & Preliminary Results on LME

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Dulal Chandra Saha, Nathan Lun, Dongwoon Huh, Rufus Ighodaro, Andrew Macwan, Norman Zhou

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Presentation Outline

ZCO-73: Forming and Joining of 3G and Hot Press Formed Steels

- Objectives
- Project Status Review
- Updates
  - Fiber Laser Welding and Heat Treatment of 3G Medium Mn Steel
- Summary

Preliminary work on liquid metal embrittlement (LME)

- LME crack formation of GI and GA coated DP980, 3G Medium Mn, press-hardened steels
- Effect of welding parameters and microstructure
- Summary and proposal for future work (ZCO-80)

Project Status

	Period / Milestones	Apr – Jun 2014	Jul – Nov 2014	Dec 2014 – May 2015	Jun 2015 – Mar 2016	Apr – Aug 2016	Sept 2016 – Mar 2017
1	Procurement of GI and GA coated HPF Steel						
2	Optimization of fiber laser welding process and fabrication of TWBs						
3	Microstructure and microhardness study of base metals and weld zones including detection of LME in HPF steel						
4	Evaluation of mechanical properties and microstructure of base metal and transverse TWB						
5	Hecker's LDH test and study of strain distribution in biaxial stretch forming						
6	Study on the effects of coating type on the weldability, microstructure and performance of TWBs						
7	ZCO-73 project reporting and initial work on LME project						

Objectives

1. To develop defects-free TWB using high speed **fiber laser welding** of **3G and HPF steels**.
2. To evaluate the **microhardness** and **tensile** properties of the TWB and its correlation to **microstructure** of the weld zones.
3. To solve manufacturing issues like **coating type** and **material combination** on the performance of the TWB.
4. To investigate the **effects of coating type**, **GI and GA**, on the **weldability** and performance of welds.
5. To study the influence of **HAZ-softening** on the properties of TWB compared to the base metal.
6. To develop an understanding of **formability** through experimental **strain distribution** across the welded blanks during deformation of TWBs in comparison to the respective monolithic sheets.

Materials – Substrate Steel Chemistry

Galvannealed (GA) HPF – 22MnB5

Gauge	C	Mn	Mo	Si	P	S	Cr	B	CE_N
1.79 mm	0.22	1.10	0.004	0.192	0.012	0.001	0.174	0.0025	0.45
1.17 mm	0.22	1.17	0.005	0.252	0.012	0.003	0.179	0.0025	0.48

Galvanized (GI) HPF – 22MnB5

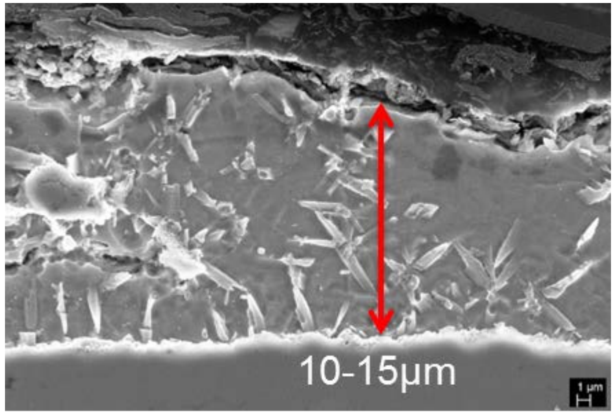
Gauge	C	Mn	Si	P	S	B	CE_N
1.19 mm	0.21	1.25	0.25	<0.01	<0.003	0.002	~0.47

Galvanized (GI) 3G – MMn

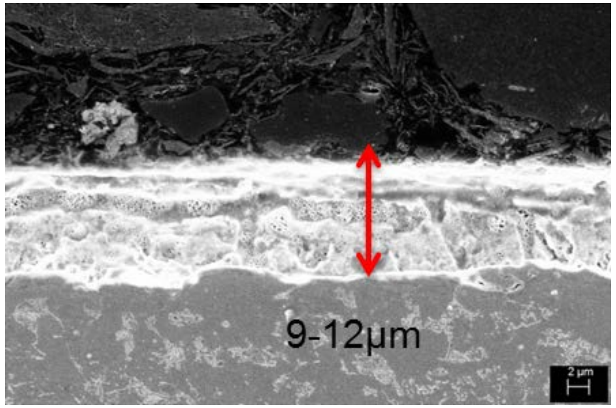
Gauge	C	Mn	Si	Al
1.46 mm	0.15	10.4	0.17	1.49

Materials – Coatings

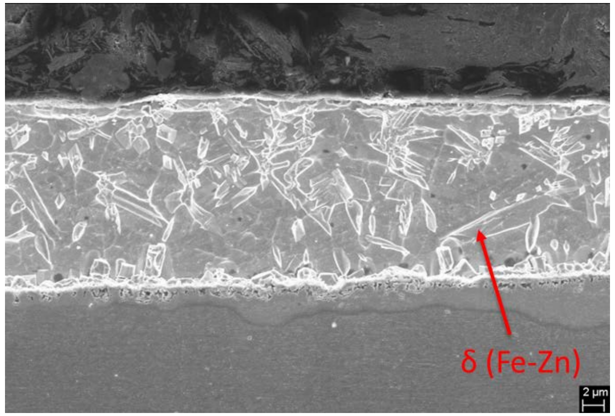
GI – 22MnB5



GA – 22MnB5

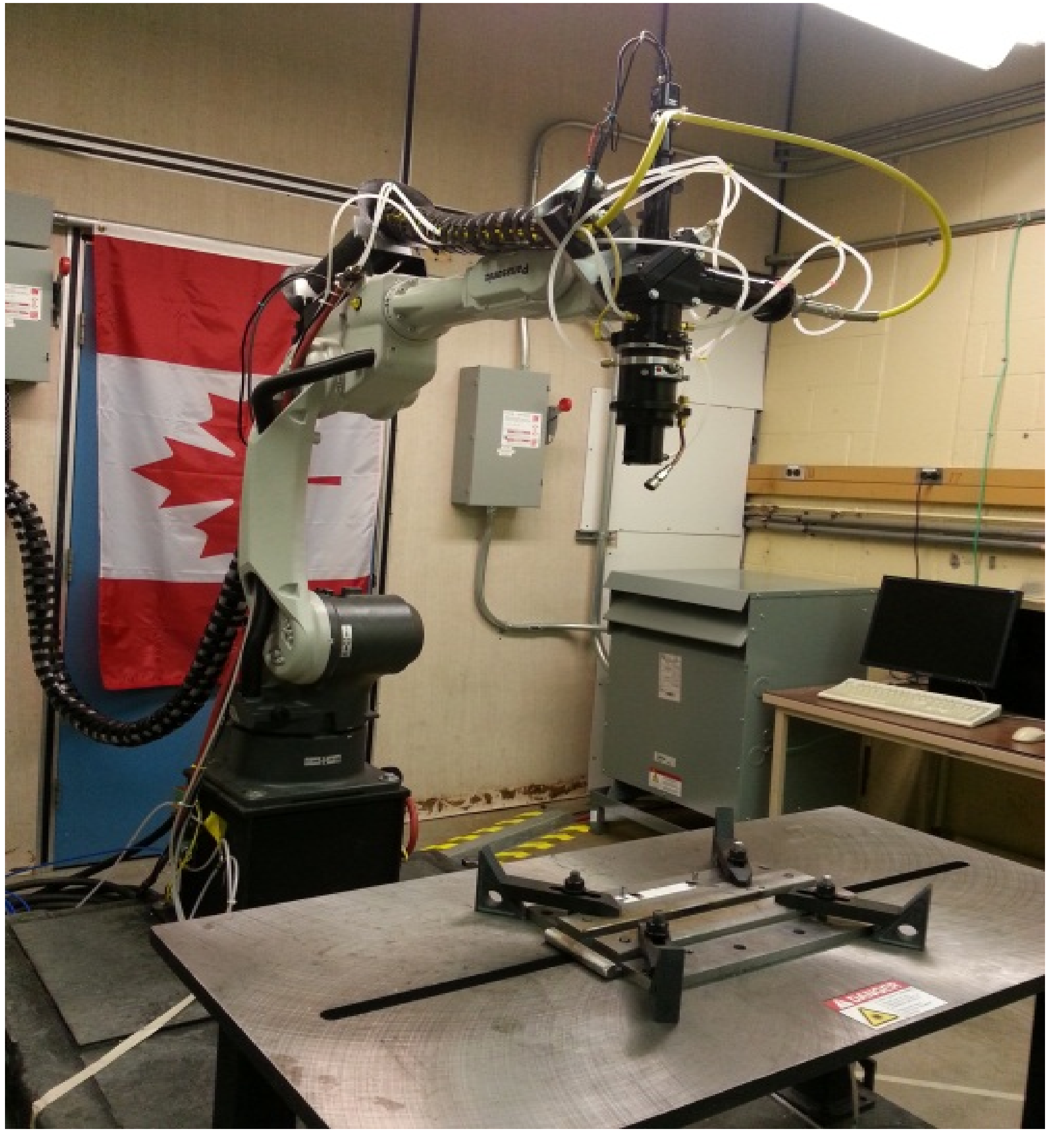


GI – MMn



Material	Gauge [mm]	Coating Weight [g/m²]			Chemistry [wt.%]		
		Top	Bottom	Total	Al	Fe	Zn
GA 22MnB5	1.79	54.8	50.2	105.0	0.27	14.1	Balance
	1.17	54.9	55.7	110.6			
GI 22MnB5	1.2	70	70	140	0.2	-	Balance
GI MMn	1.46	50	50	100	~0.2	-	Balance

Equipment – Fiber Laser Welder



IPG Photonics YLS-6000 Fiber Laser

- Maximum Deliverable Power: 6kW
- Maximum Travel Speed: 24m/min
- Fiber Core Diameter: 0.3mm
- Beam Spot Diameter: 0.6mm
- Welding direction: 25° backward

Laser Mechanisms Welding Head

- Focal Length: 200 mm
- Air Knife Pressure: 100 psi

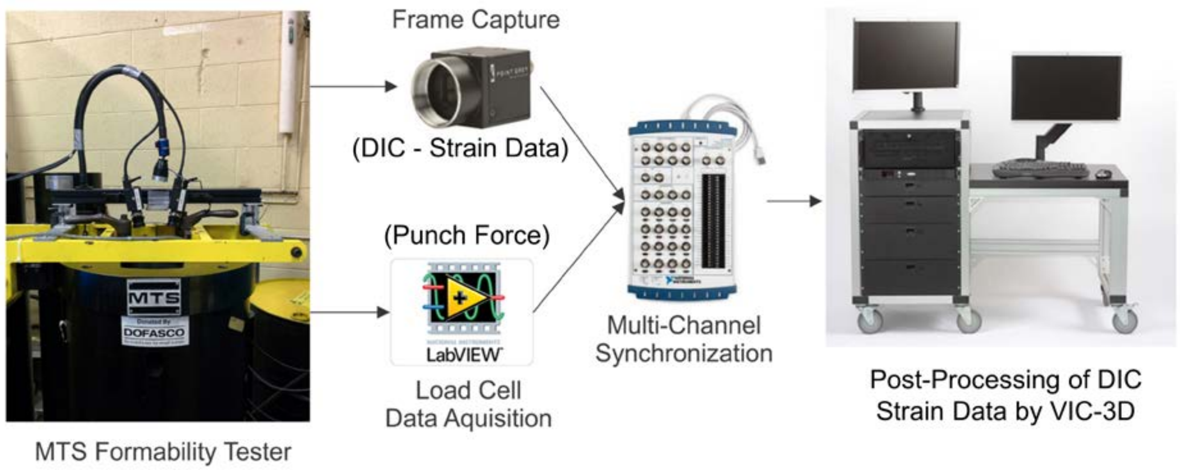
6-axis TA1600 Panasonic Robot

- **Shielding Gas**
- Type: 99.999% UHP Argon
- Lead Assist: 30CFH (~14.2 LPM)
- Backshield: 45CFH (~21.2 LPM)

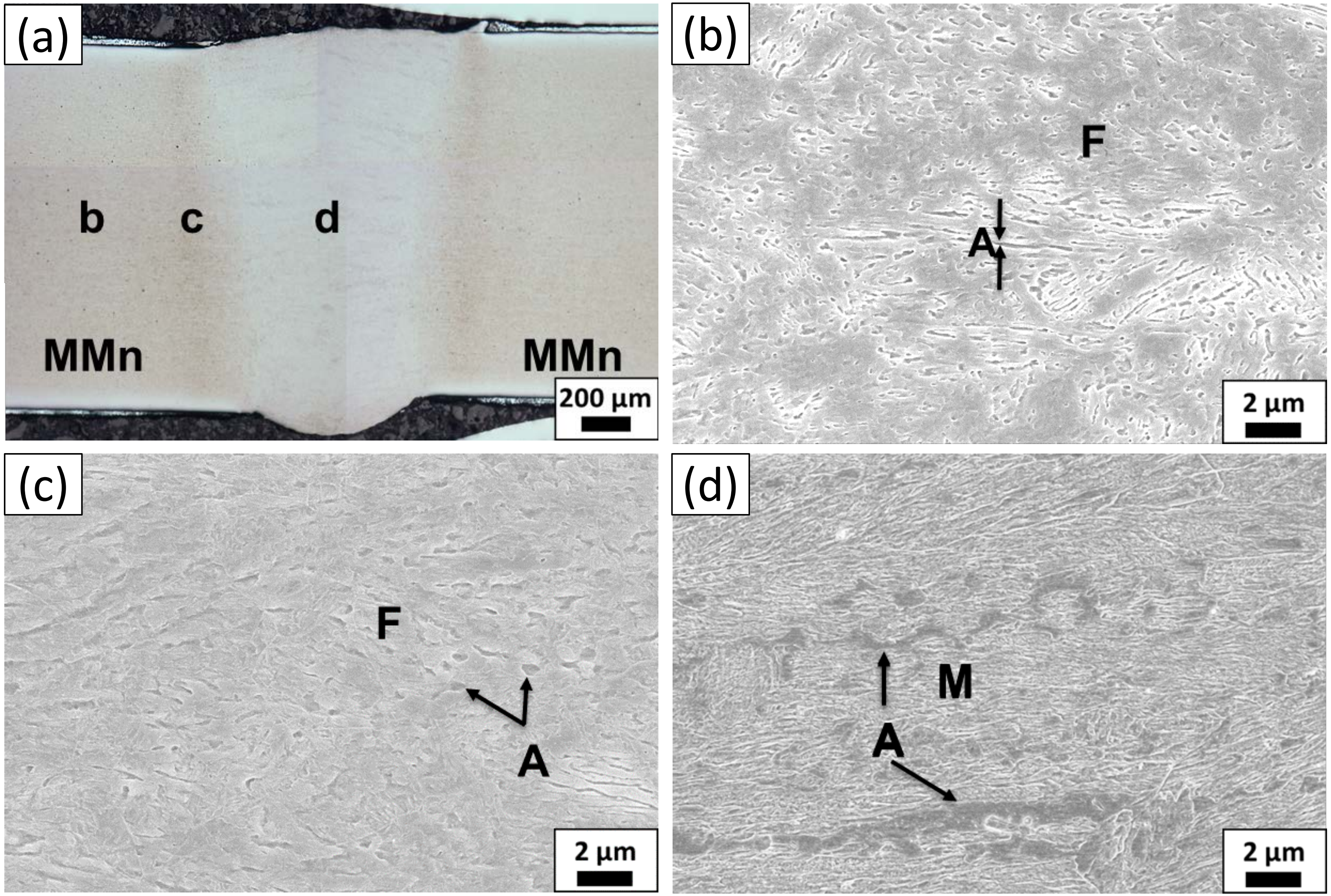
Equipment – Mechanical Testing

- **Tensile**
  - Strain Rate Control: 0.001 to 0.1 mm/mm/s
  - Cross Head Speed Control: 1 mm/min, 10 mm/min

- **Formability (MTS 866 Dome Tester)**
  - Hemispherical punch (101.6 mm punch diameter)
  - 550 kN clamp force
  - 132 mm draw bead diameter
  - Punch velocity = 0.2 mm/s
  - **3D Digital Image Correlation**
  - Step size = 5
  - Subset size = 35
  - Strain filter = 11 (Hencky)
  - Non-incremental correlation (projection error <0.1)

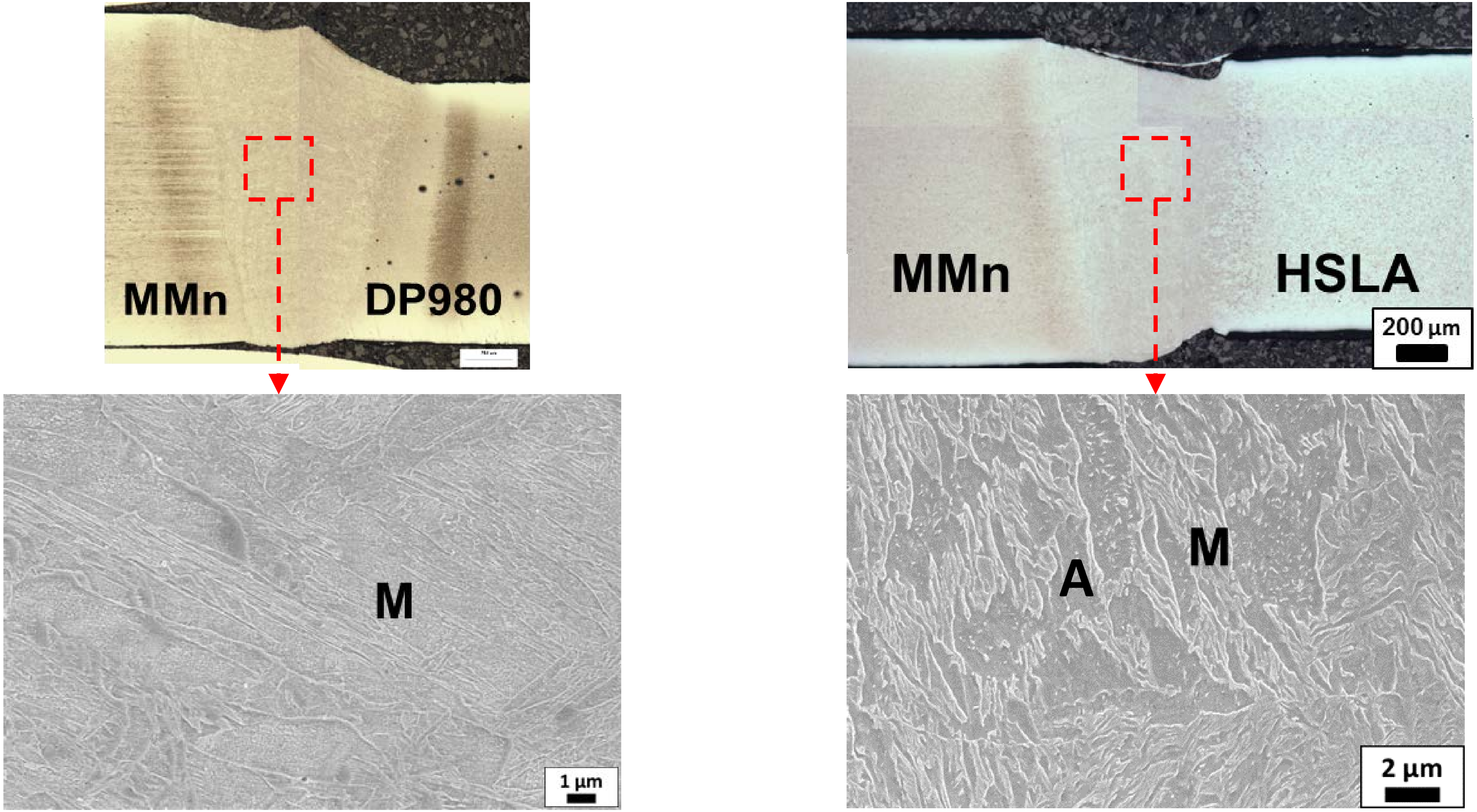


Similar Welds – MMn to MMn



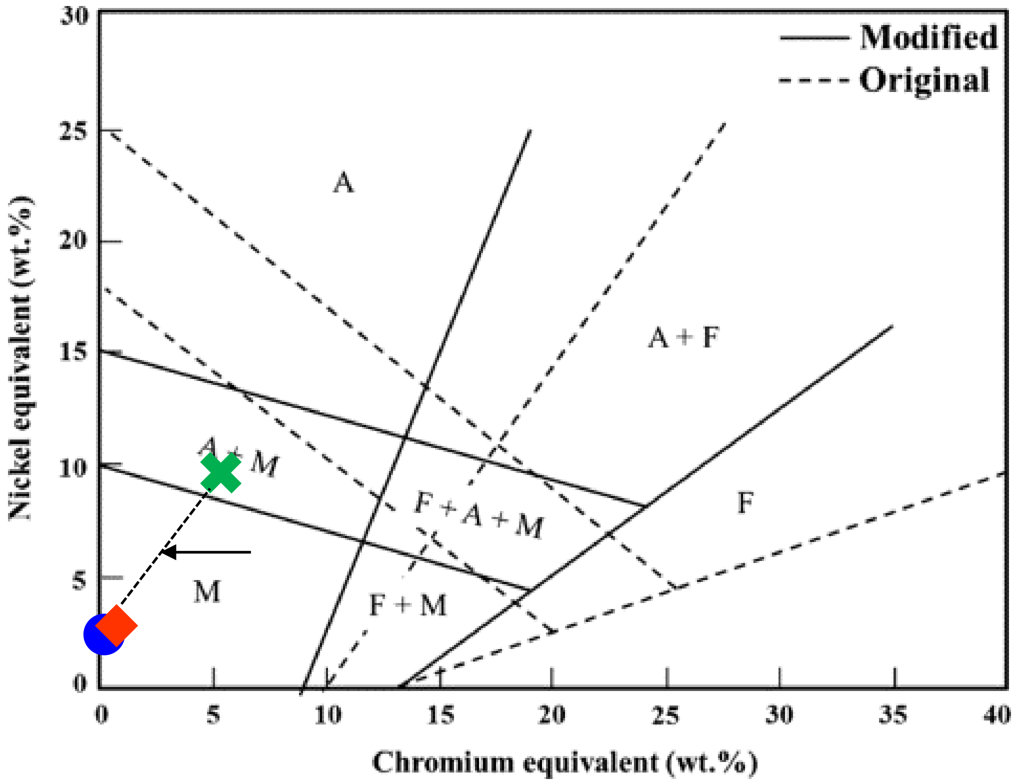
- **(b) BM:** Ferrite and Austenite
- **(c) HAZ:** Ferrite and Austenite
- **(d) FZ:** Austenite and Martensite

Dissimilar Welds



Fusion Zone Microstructure Prediction

- Modified Schaeffler Diagram



[R.L., Kluehm P.J., Maziasz, E.H. Lee, *Mater. Sci. Eng. A* 102 (1988) 115-124.]

	MMn ✖	HSLA ●	DP980 ◆	MMn-HSLA	MMn-DP980
Cr_{eq}	5.71	0.49	1.34	3.36	3.75
Ni_{eq}	9.87	2.09	3.85	6.37	7.17

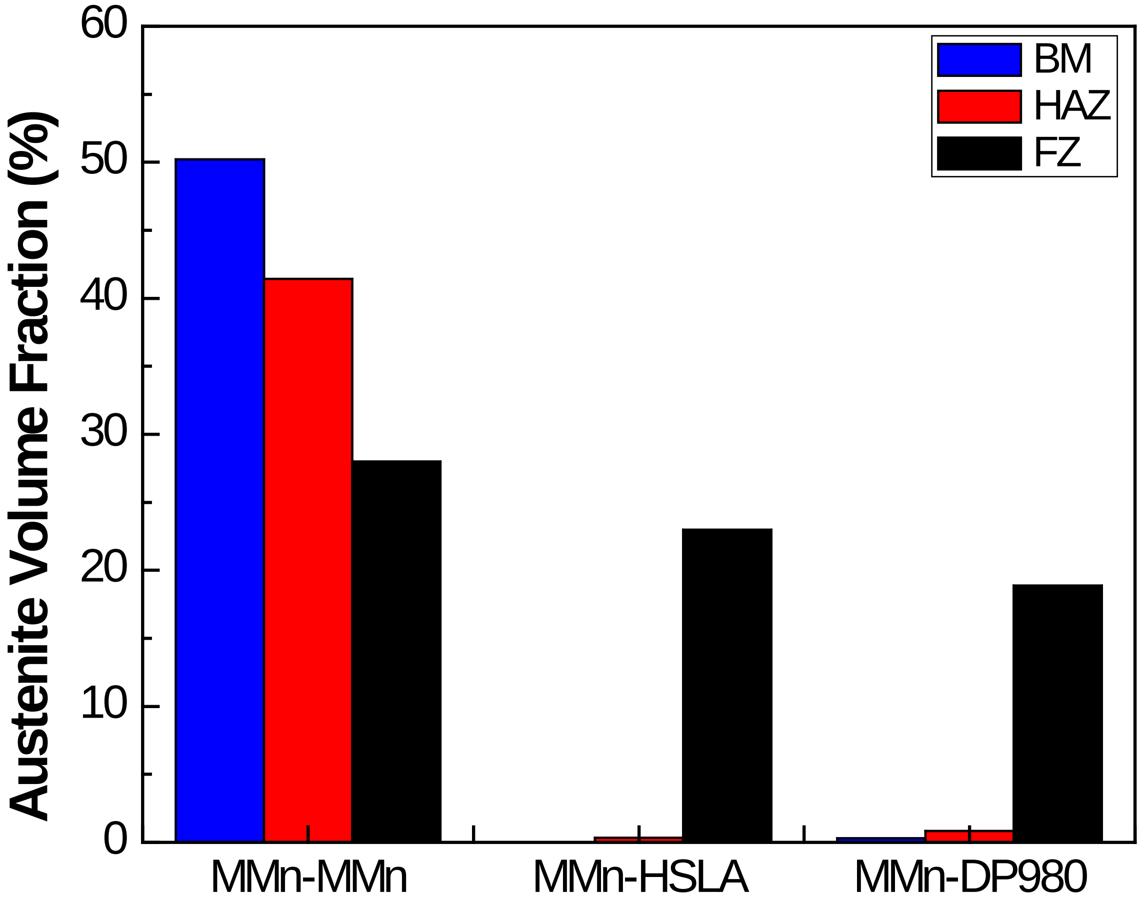
- Schaeffler's diagram modified for the Mn stabilization of γ-Fe
- Assuming FZ dilution is equivalent to 1.23:1 (MMn: HSLA/DP980), FZ microstructure was expected to be martensitic

$$Ni_{eq} = Ni + Co + 0.5Mn + 0.3Cu + 30C + 25N$$

$$Cr_{eq} = Cr + 2Si + 3.5Al + 1.5Mo + 5V + 1.75\mathrm{Nb} + 1.5\mathrm{Ti} + 0.75\mathrm{W}$$

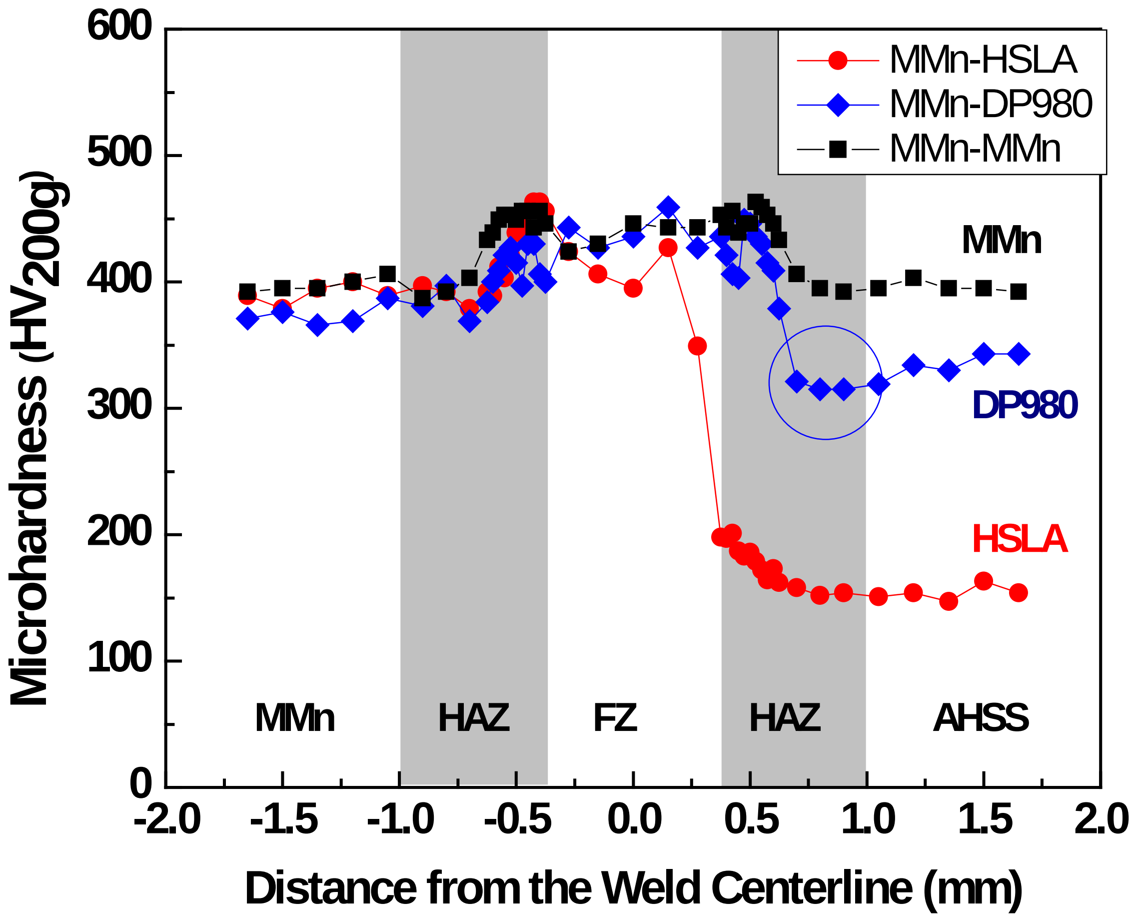
[S. Lee, C-Y. Lee, Y-K. Lee, *Journal of Alloys and Compounds,* 628 (2015) 46-49.]

X-Ray Diffraction Analysis of Volume Fraction of Austenite



- **MMn-MMn:**
  - BM – about 50% austenite
  - HAZ – reduction of austenite caused by solid state transformation
  - FZ – reduction of austenite volume caused by fast cooling rate and transformation to martensite
- **MMn-HSLA:**
  - BM – HSLA BM contains no austenite
  - HAZ – Contains very little austenite (could be error)
  - FZ – high volume fraction of austenite (incomplete mixing of the steel chemistry)
- **MMn-DP980:**
  - BM- DP980 - contains a little austenite
  - HAZ – Contains a little more austenite
  - FZ – Same as HSLA, but lower austenite volume fraction.

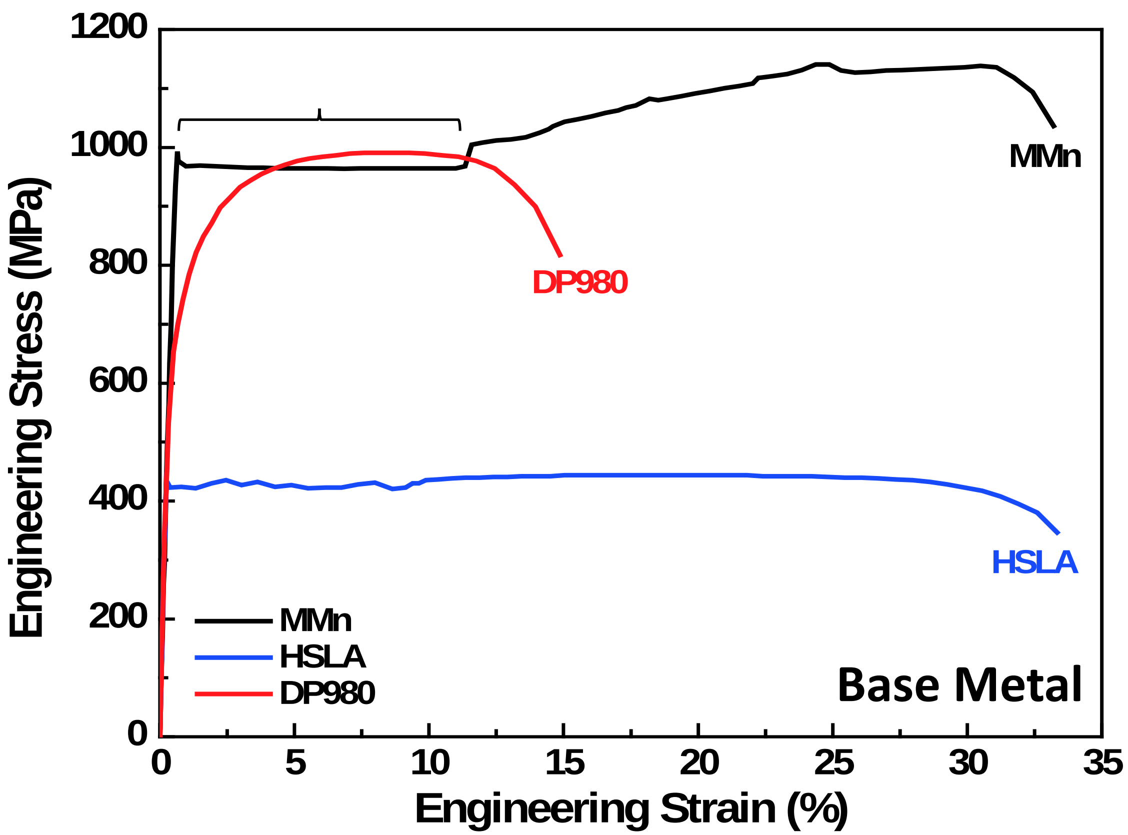
Microhardness Distribution

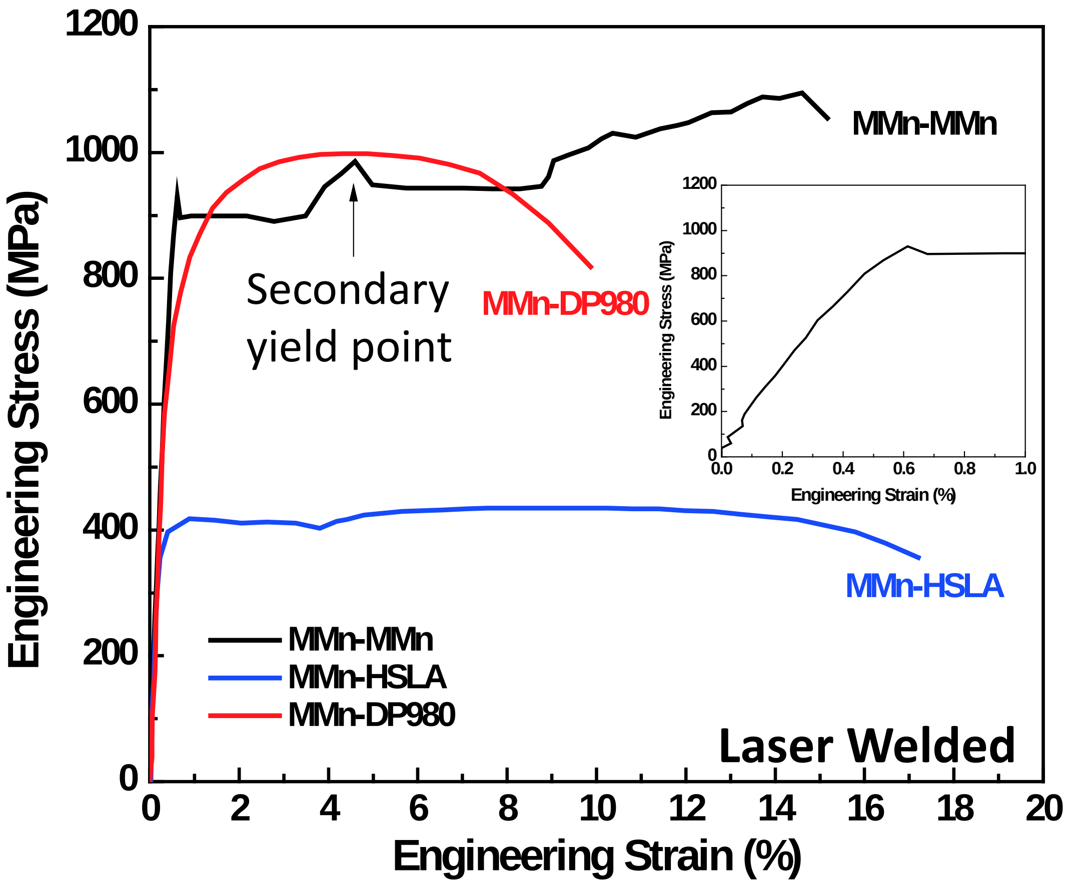


TWB	Microhardness (HV_{200g})		
	BM	FZ	$\Delta HV_{FZ\text{-}BM}$
MMn-MMn	396	445	49
MMn-DP980	343	425	82
MMn-HSLA	155	431	276

- Similar welds of 3G material result in the smallest difference between the FZ and BM hardness with minimal HAZ softening
- MMn-DP980 exhibits a small local decrease in hardness in the HAZ

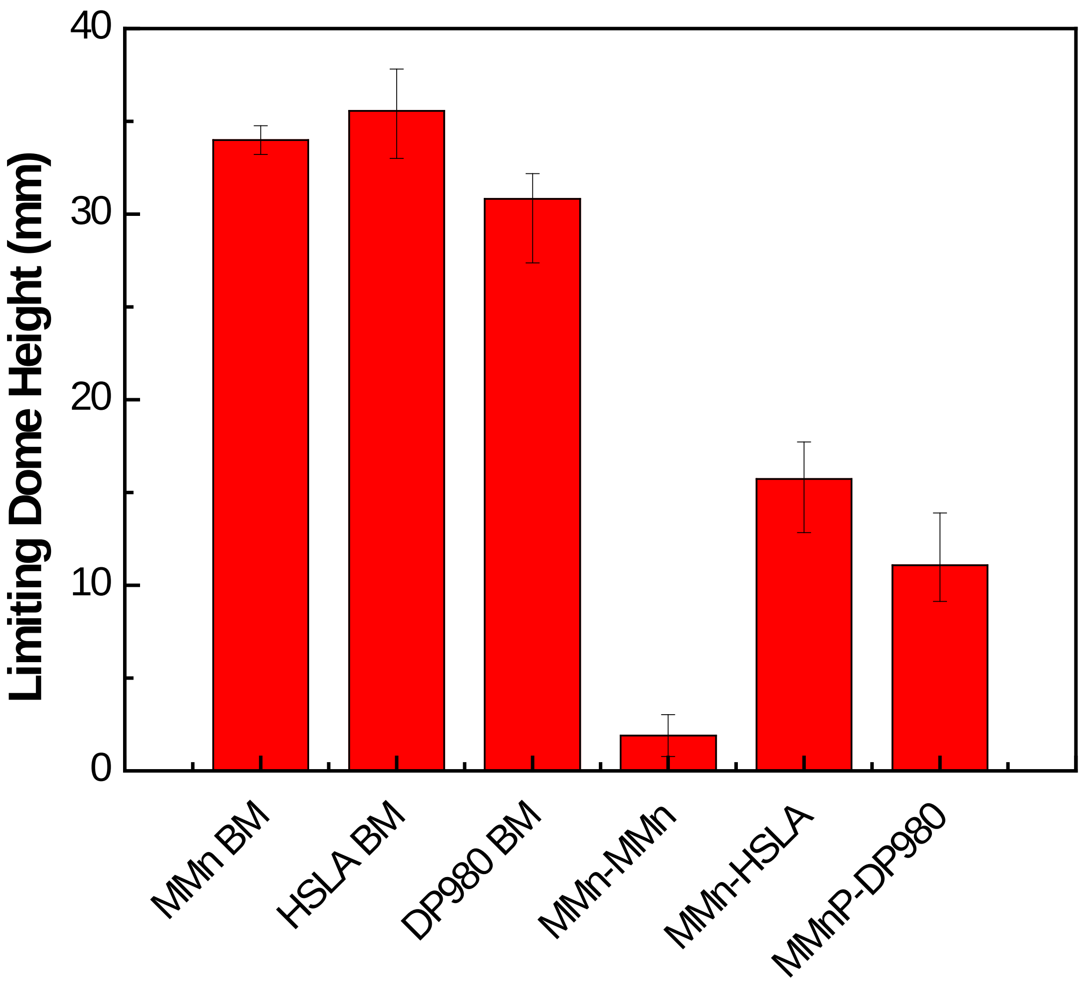
Tensile Testing

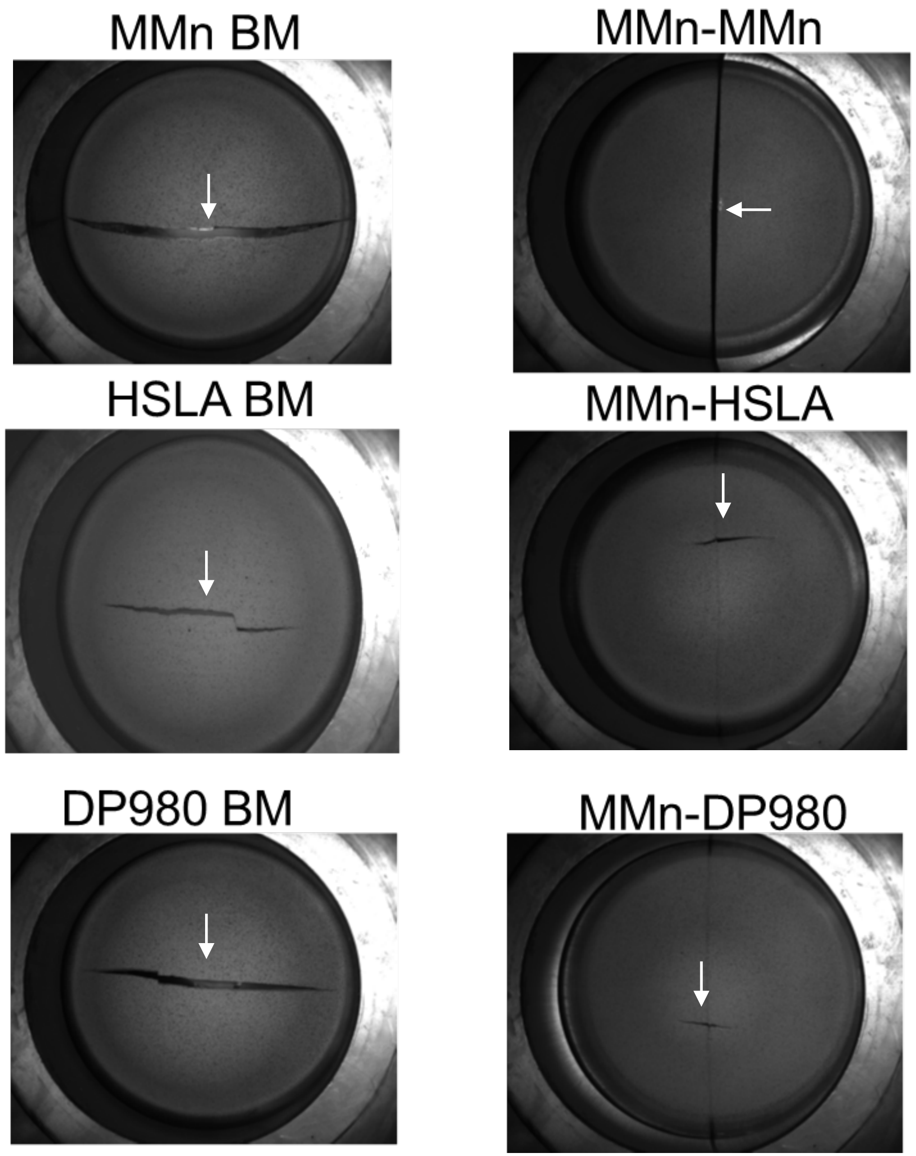




- MMn-MMn similar weld shows a secondary yield point phenomena; associated with hard fusion zone material

Formability Testing

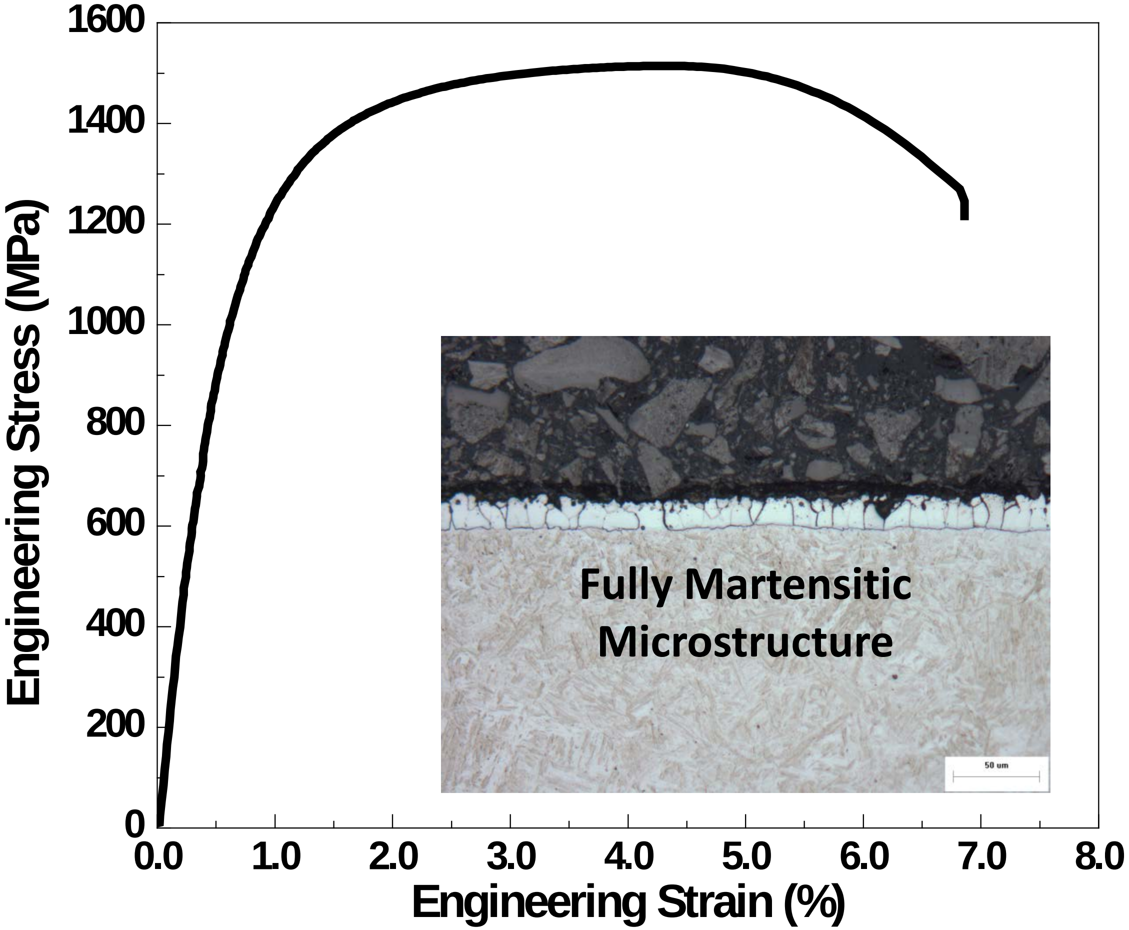




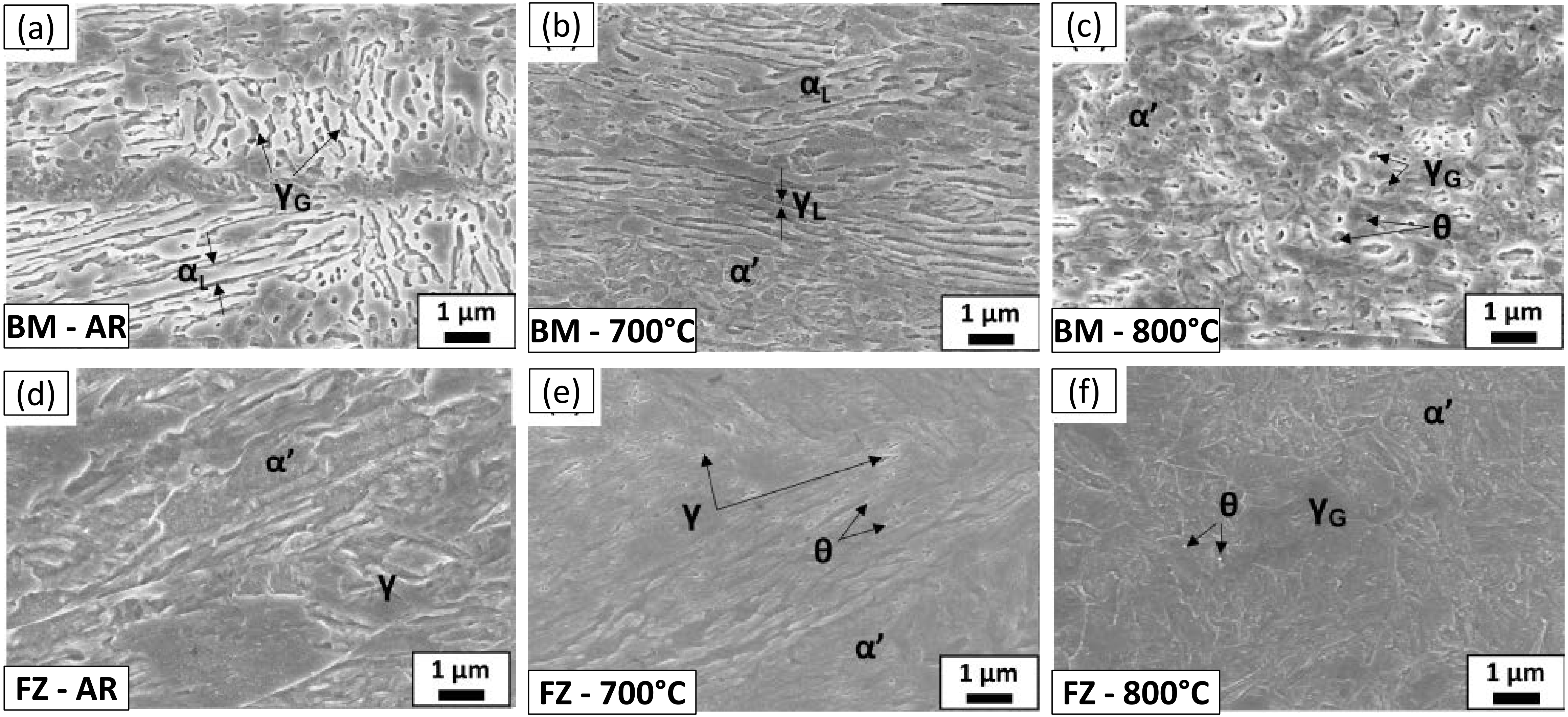
MMn Steel as Press-hardening Applications

- Boron containing USIBOR® or press-hardened steel exhibits high strength (UTS = 1.5 - 2 GPa), but limited ductility.
- Steels with low ductility have a tendency of sudden failure.
- Laser welded blanks of MMn steels were heat treated to investigate the viability of their usage as a potential steel for press hardening applications.

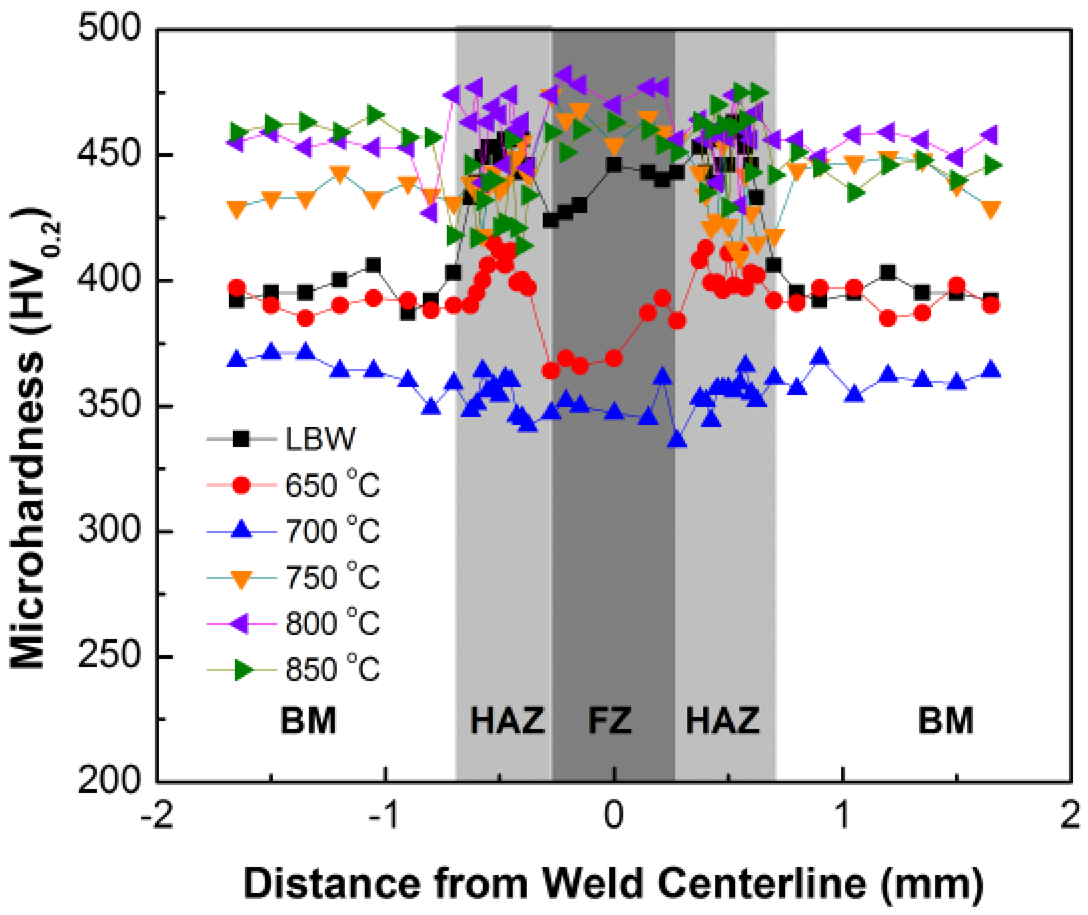
GA-coated USIBOR®

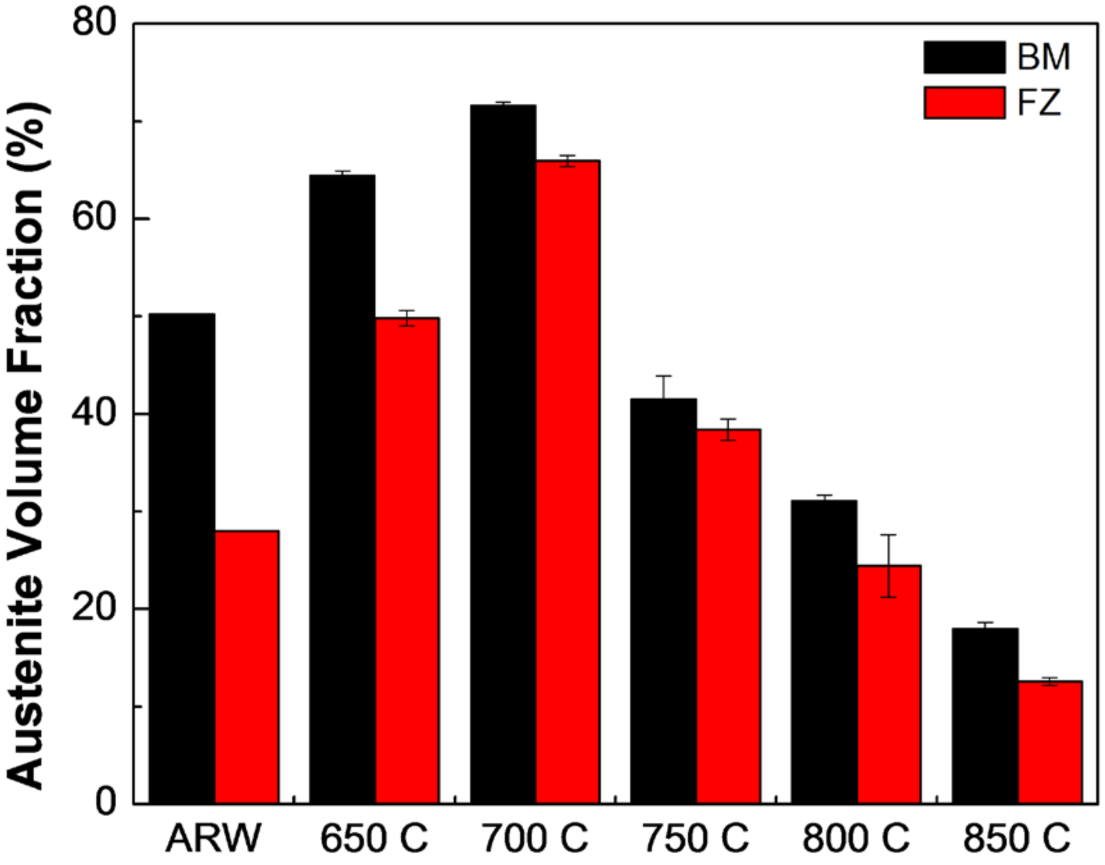


Heat Treatment of LWBs Medium Mn Steels

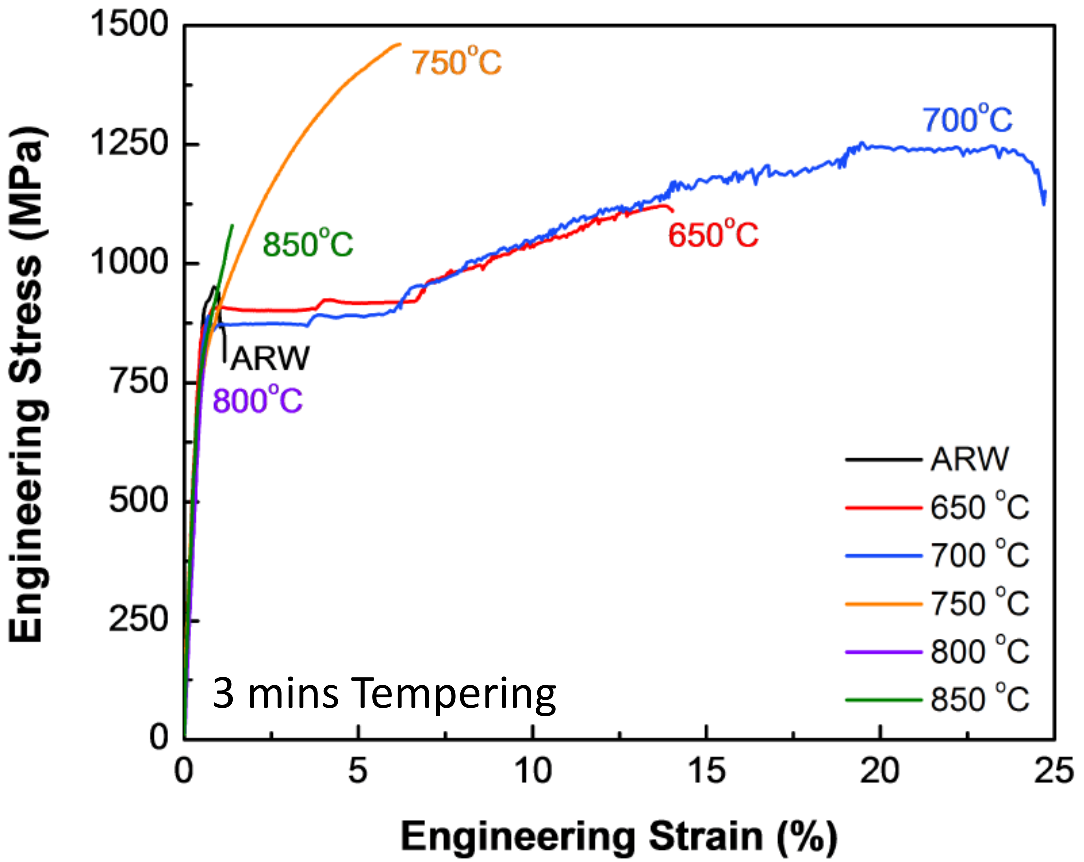


Microhardness and Volume fraction of Austenite





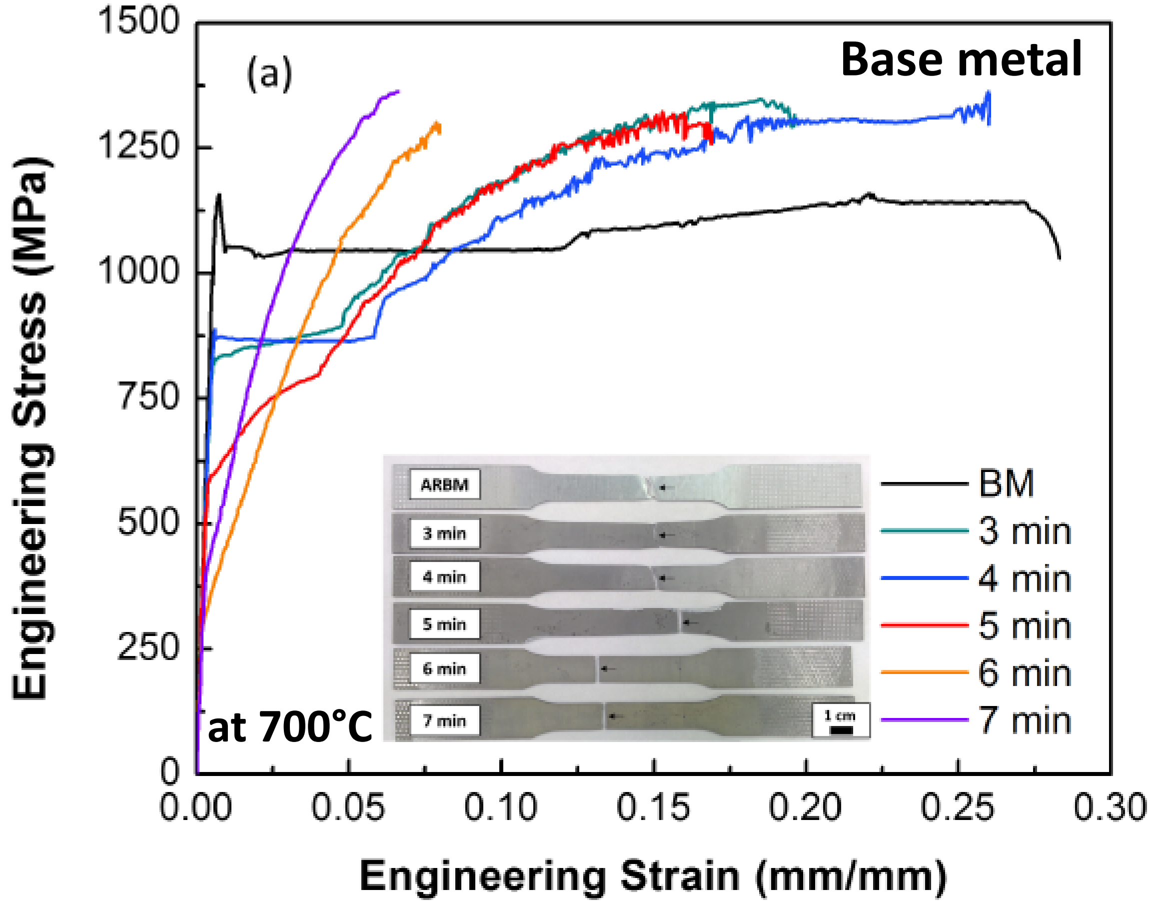
Tensile Properties of LWBs MMn at Press-Hardened condition

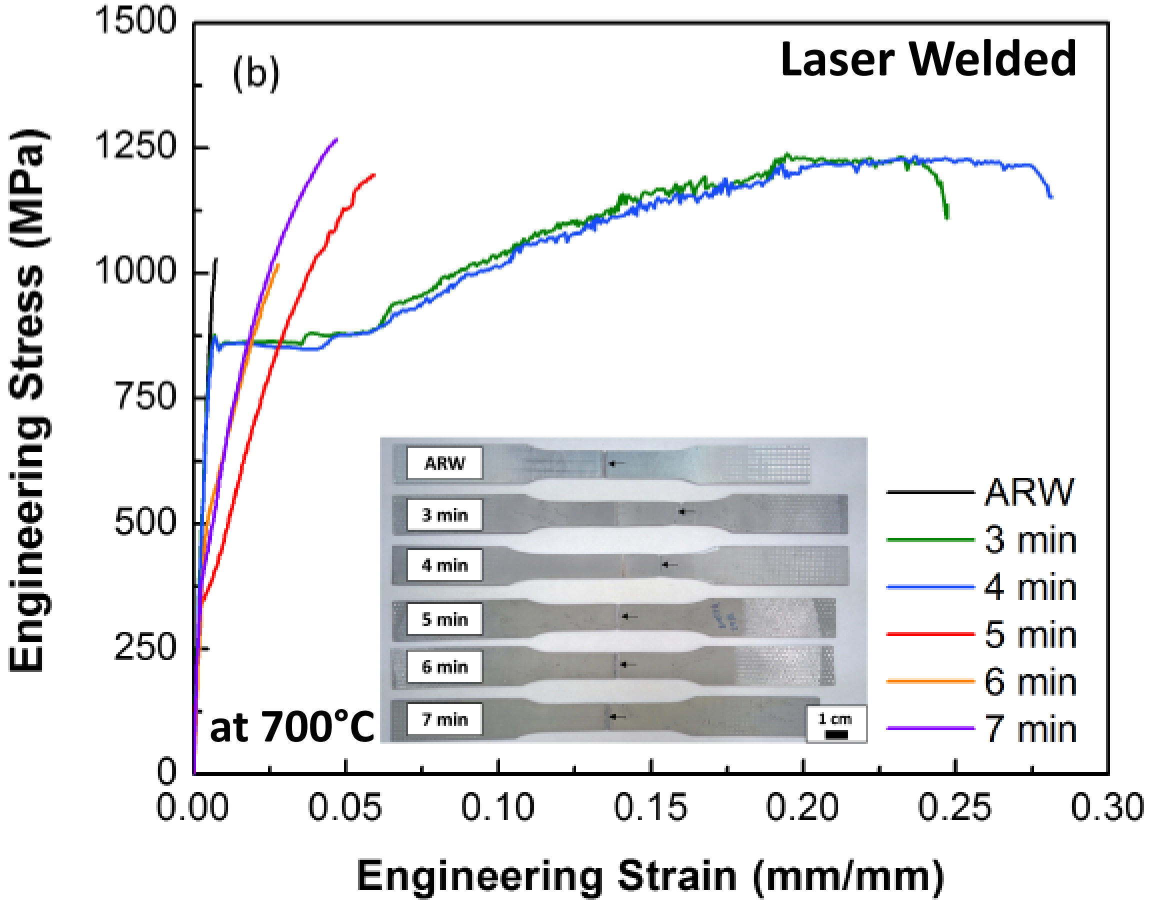


Sample Condition	UTS (MPa)	Total Elongation (%)	UTS x TEL (MPa·%)
ARW	951 ± 15	1.1 ± 0.3	1,046
650 °C	1116 ± 13	14.0 ± 0.6	15,622
700 °C	1356 ± 28	15.6 ± 0.2	21,228
750 °C	1473 ± 12	5.4 ± 0.9	7,878
800 °C	986 ± 13	0.7 ± 0.4	670
850 °C	1110 ± 30	1.4 ± 0.0	1,554

- At 650°C, the laser welded specimen recovers a substantial amount of ductility over the ARW.
- At a heat treatment temperature of 750°C, the yield point elongation is completely eliminated.
- 700°C was identified as the best potential heat treatment parameter.

Effect of Press-hardening Time





- Heat treatment effectively reduced the yield point elongation, raised the UTS and reduced the total achievable strain with increasing soak time.
- The tensile specimens show that fracture in the BM region outside of the weld occurs for 3 and 4 minutes

Summary on ZCO-73

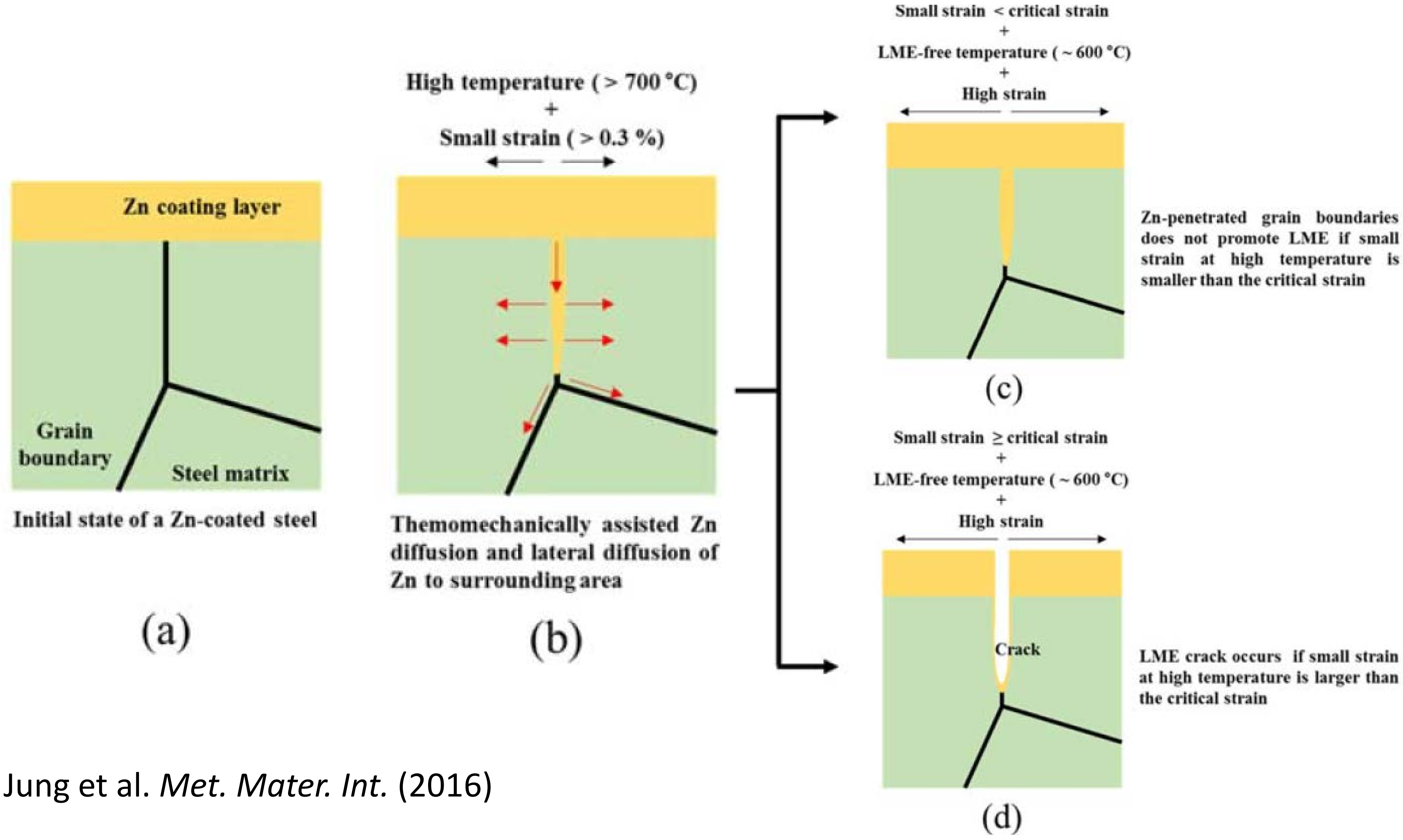
- Fiber laser welding process optimization was performed on MMn steel to produce **defect free welds**
- Microstructure characterization and hardness testing was performed on cross sections of **similar and dissimilar MMn steel joints**
- Tensile and formability testing was conducted to assess the effect of laser beam welding of **MMn-MMn, MMn-DP980 and MMn-HSLA** TWBs
- Joint **ductility was significantly improved** by heat treating the joint at **700°C for 3 and 4 minutes** followed by quenching.
- The heat treatment temperature and **soak time for this MMn steel is lower** and shorter than that of conventional C-Mn-Si press-hardened steels.
- **Prolonged holding time produces an extremely brittle joint** due to destabilization of the austenite; this suggests that the heat treatment window is fairly narrow.

New Research Direction on Zinc Effects on Mechanical Behavior of AHSS Welds

Outline of LME Project

- Develop an understanding on the susceptibility of AHSS to LME through **thermomechanical testing of various zinc coating compositions**
- Experimentally quantify and validate **numerical models** of the stress fields present at the RSW joint
- Investigate in detail the contribution thresholds of different spot welding parameters required to induce LME cracking in AHSS
- Correlate the mechanical properties to the onset of LME in AHSS spot welds with respect to tensile shear and cross tension loading under ambient temperature
- Develop appropriate spot weld parameter **guidelines** for the **mitigation and remediation of LME cracks** in AHSS

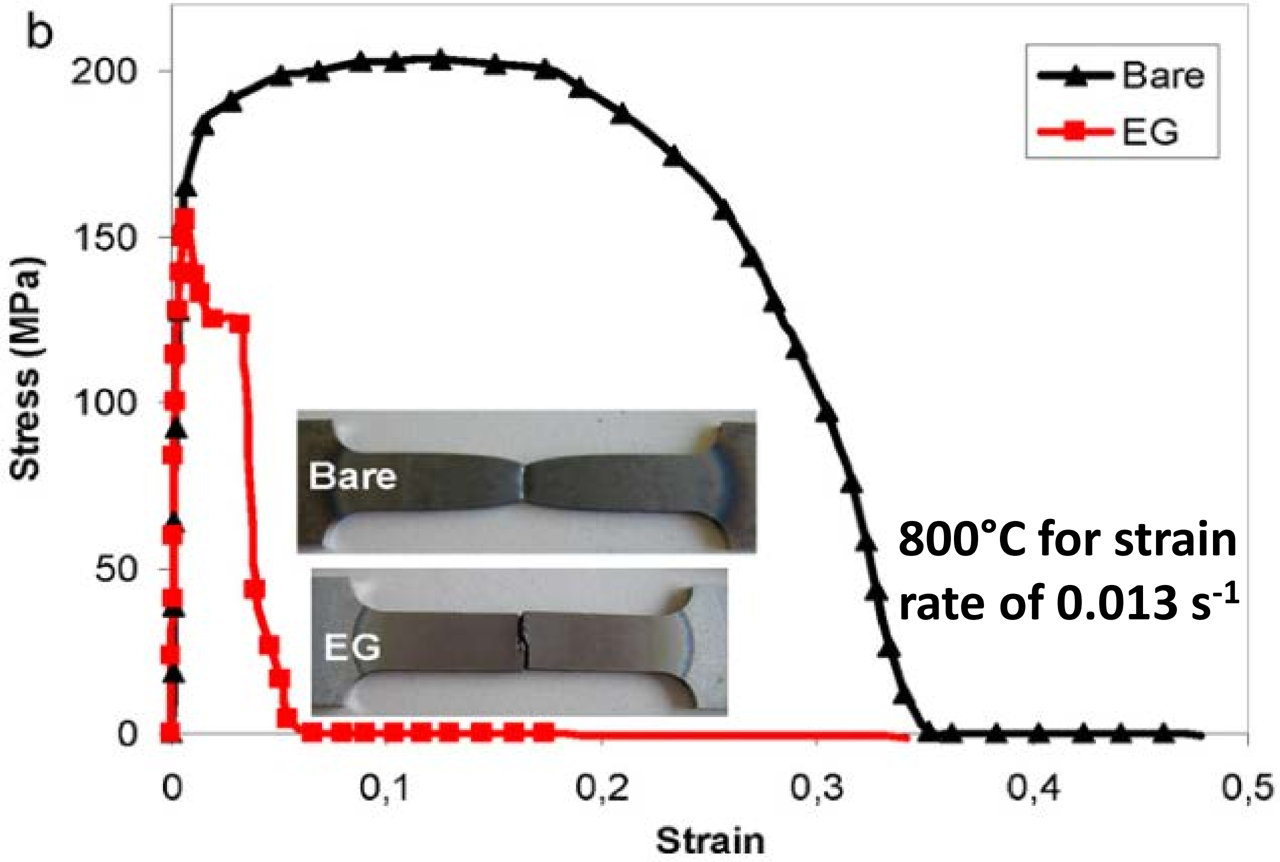
Liquid Metal Embrittlement (LME)



Jung et al. *Met. Mater. Int.* (2016)

Influences of LME on Mechanical Behavior

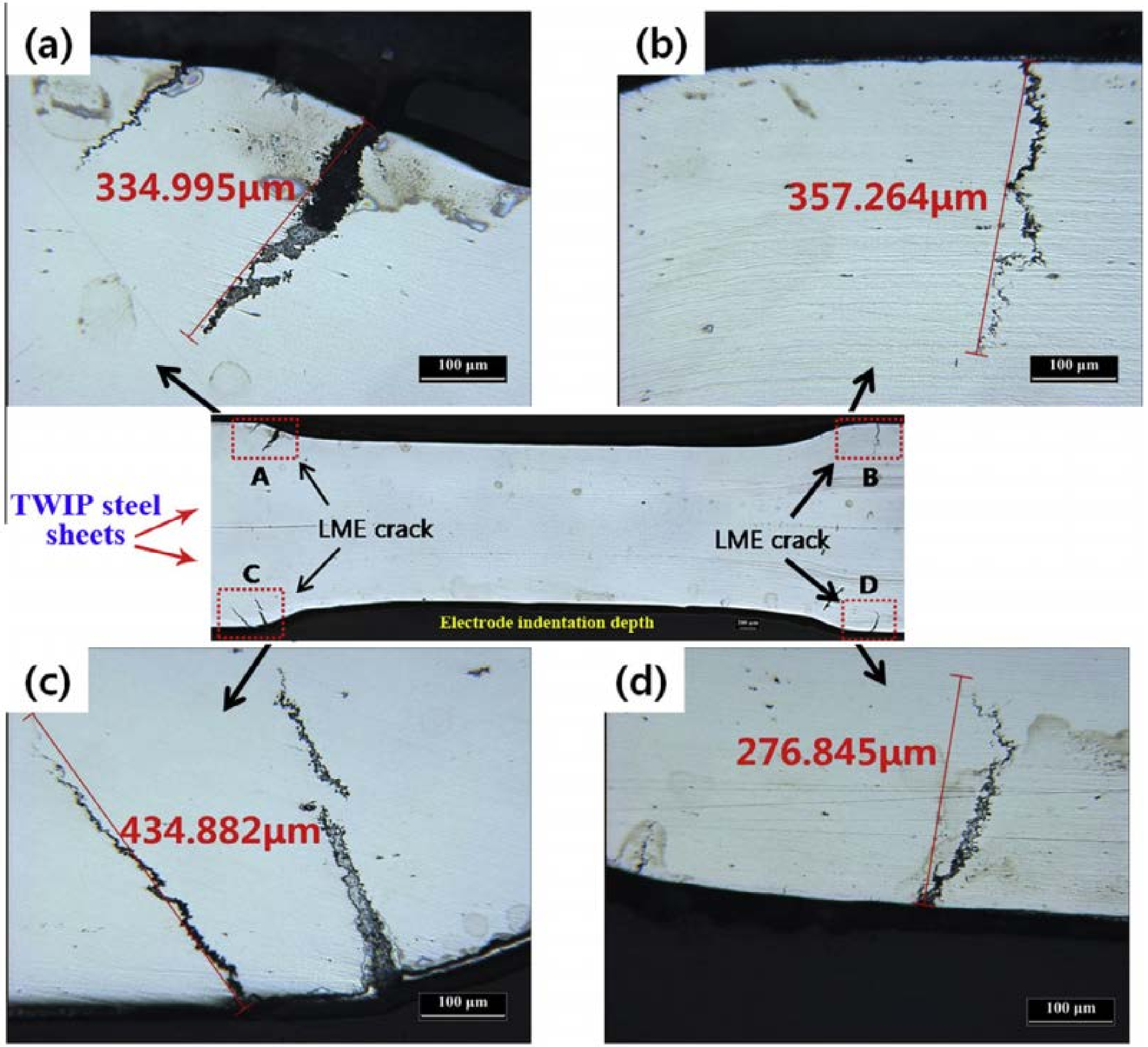
Tensile curves of Fe22Mn0.6C TWIP steel

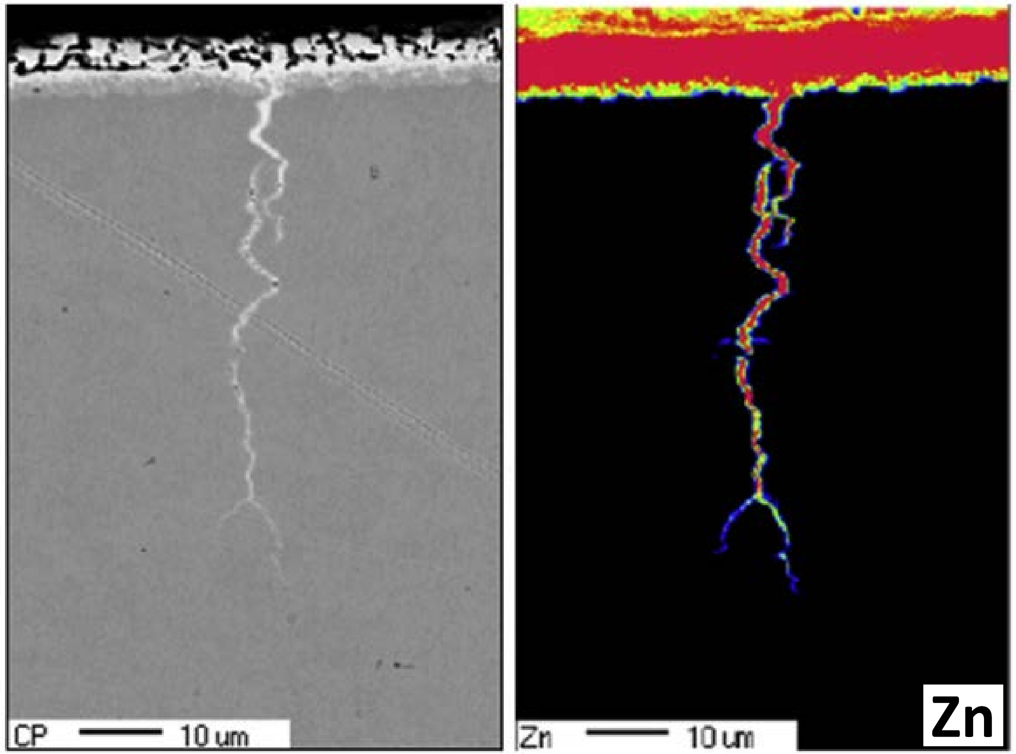


800°C for strain rate of 0.013 s^{-1}

- LME has a deleterious effect on steel since the onset of premature crack initiation and propagation along grain boundaries leads to a significant reduction in maximum achievable stress and ductility

LME Cracks During Resistance Spot Welding





Ashiri et al. *Scripta. Mat.* (2015)

Main Factors Involves on LME Cracks

- Liquid Zinc (e.g. Zinc Coating)
- Microstructure, grain size and distribution, chemistry (e.g. austenitic microstructure has more tendency to LME cracks)
- Thermal stress generated during RSW → **Our Concerns**

Thermal stress can be correlated with the welding process and parameters:

- Electrode tip shape and size
- Electrode force and alignment
- Fixturing and part fit-up
- Welding current and time
- Cooling rate
- Welding schedule profile

LME Crack Controlling Factors

- The following factors need to be accounted for:

  - Shorter reaction time between the liquid zinc and steel substrate prior to apply stress – can be controlled by optimizing the weld cycle profile.

  - The reaction barrier between the zinc coating and the steel substrate – this is the coating manufacturer issue to deal with the inhibition layers in the steel coatings

  - Controlling the thermal stress generated during RSW which are related to the welding parameters.

Materials and Coatings

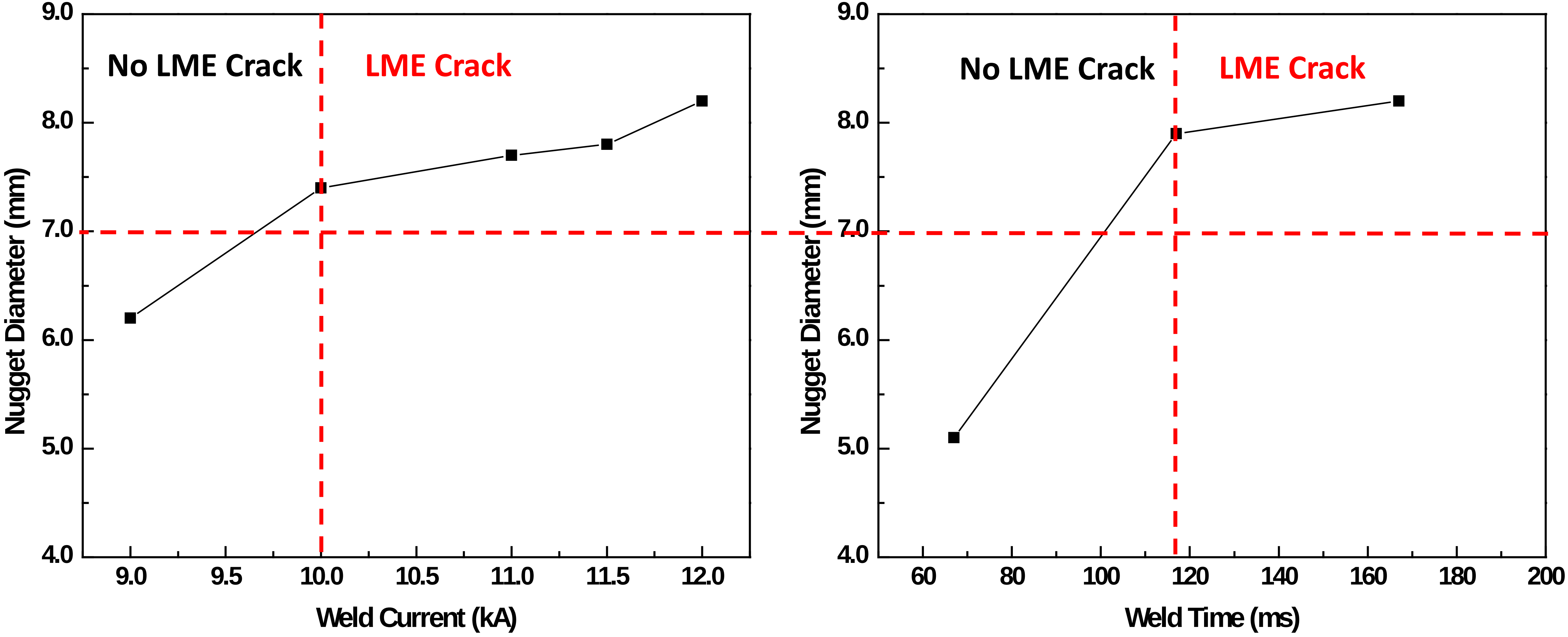
- Materials

Materials	Gauge [mm]	C	Mn	Mo	Si	P	Al	Cr	B
GA – 22 MnB5	1.20	0.22	1.17	0.005	0.252	0.012	-	0.179	0.0025
GI – DP980	1.20	0.15	1.5	-	0.3	-	0.05	-	-
GA – DP980	1.20	0.10	2.2	0.2	0.3	-	0.04	0.2	-
GI – MMn	1.45	0.15	10.4	-	0.17	-	1.49	-	-

- Coatings

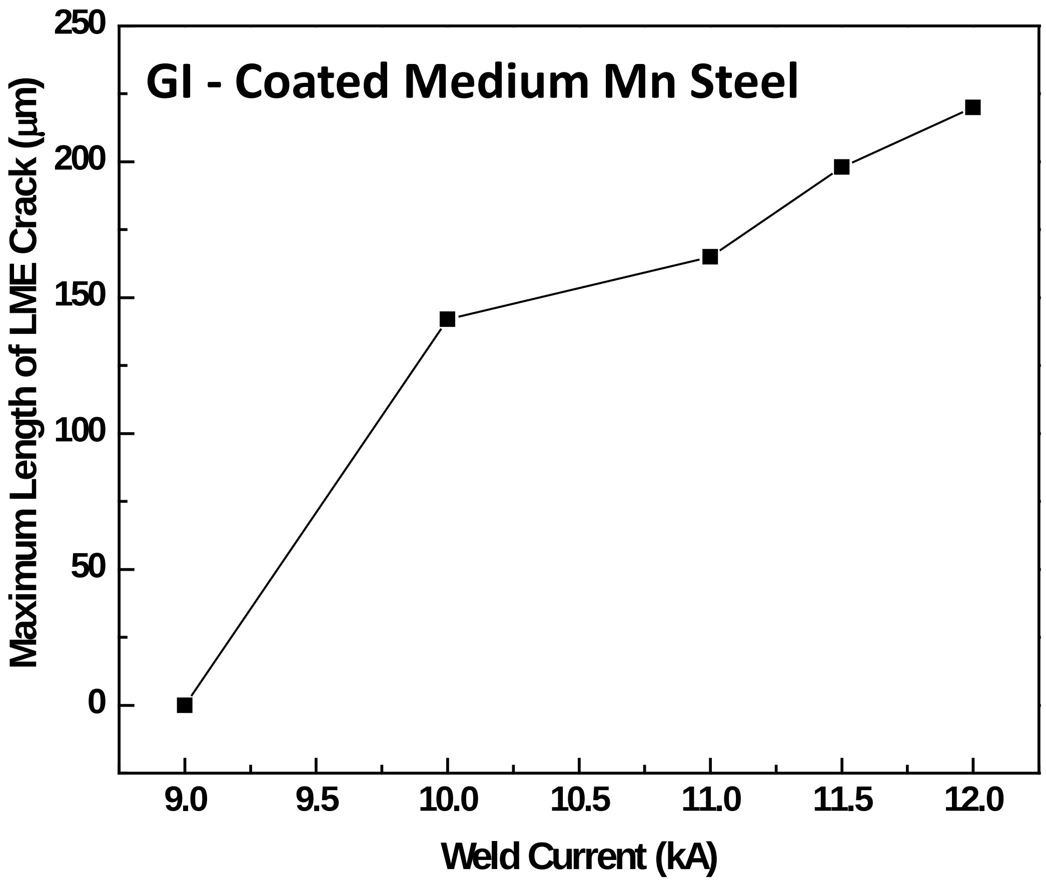
Material	Coating Weight [g/m^2]			Chemistry [wt.%]		
	Top	Bottom	Total	Al	Fe	Zn
GA - 22MnB5	54.9	55.7	110.6	0.27	14.1	Balance
GI – DP980	60	55	115	-	0.03	Balance
GA – DP980	41	55	96	-	11	Balance
GI – MMn	50	50	100	~0.2	-	Balance

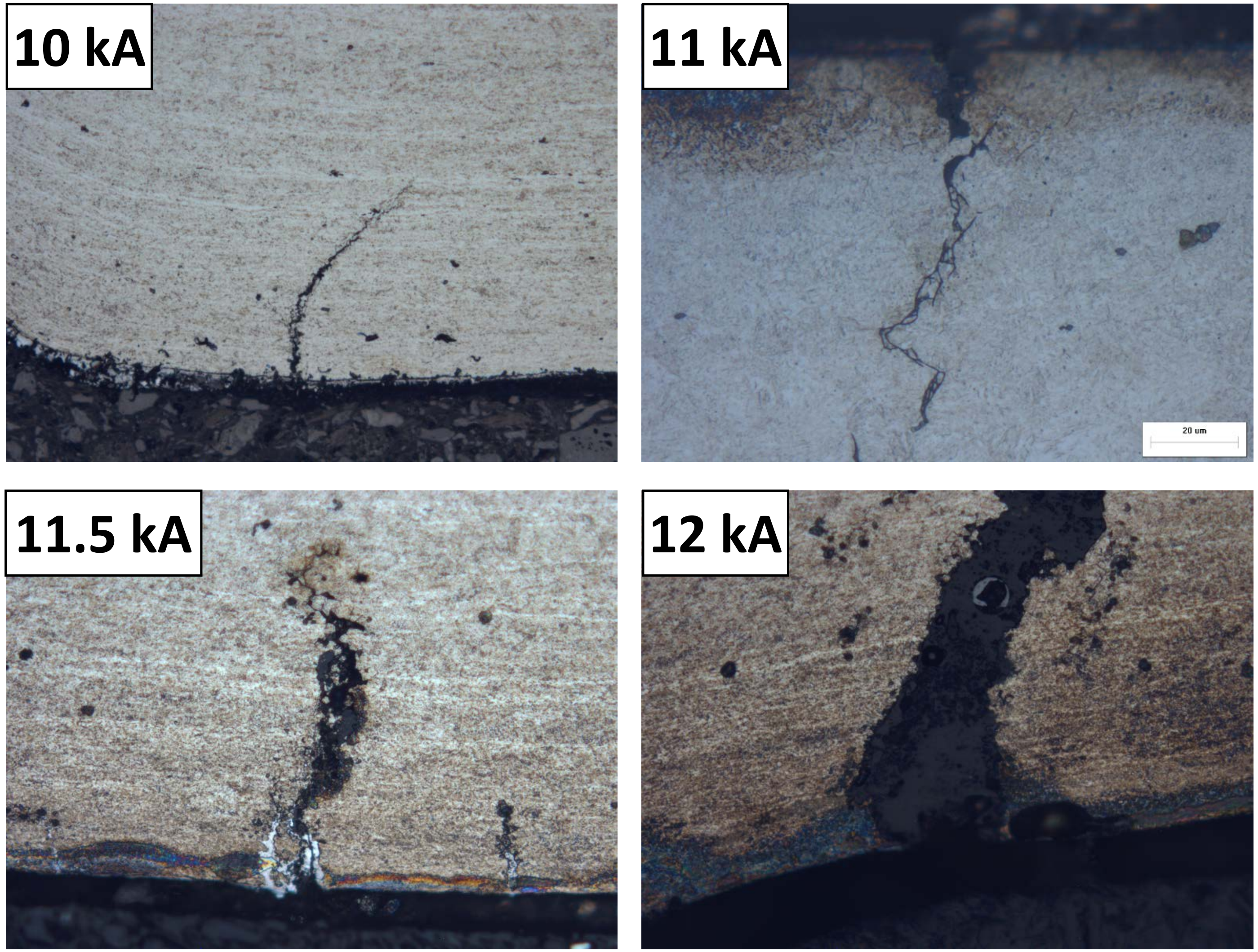
GI - Coated Medium Mn Steel



- Welding schedule was selected according to AWS D8.9 standard
- LME cracks were found on all welds when nugget diameter exceeds approximately 7.0 mm

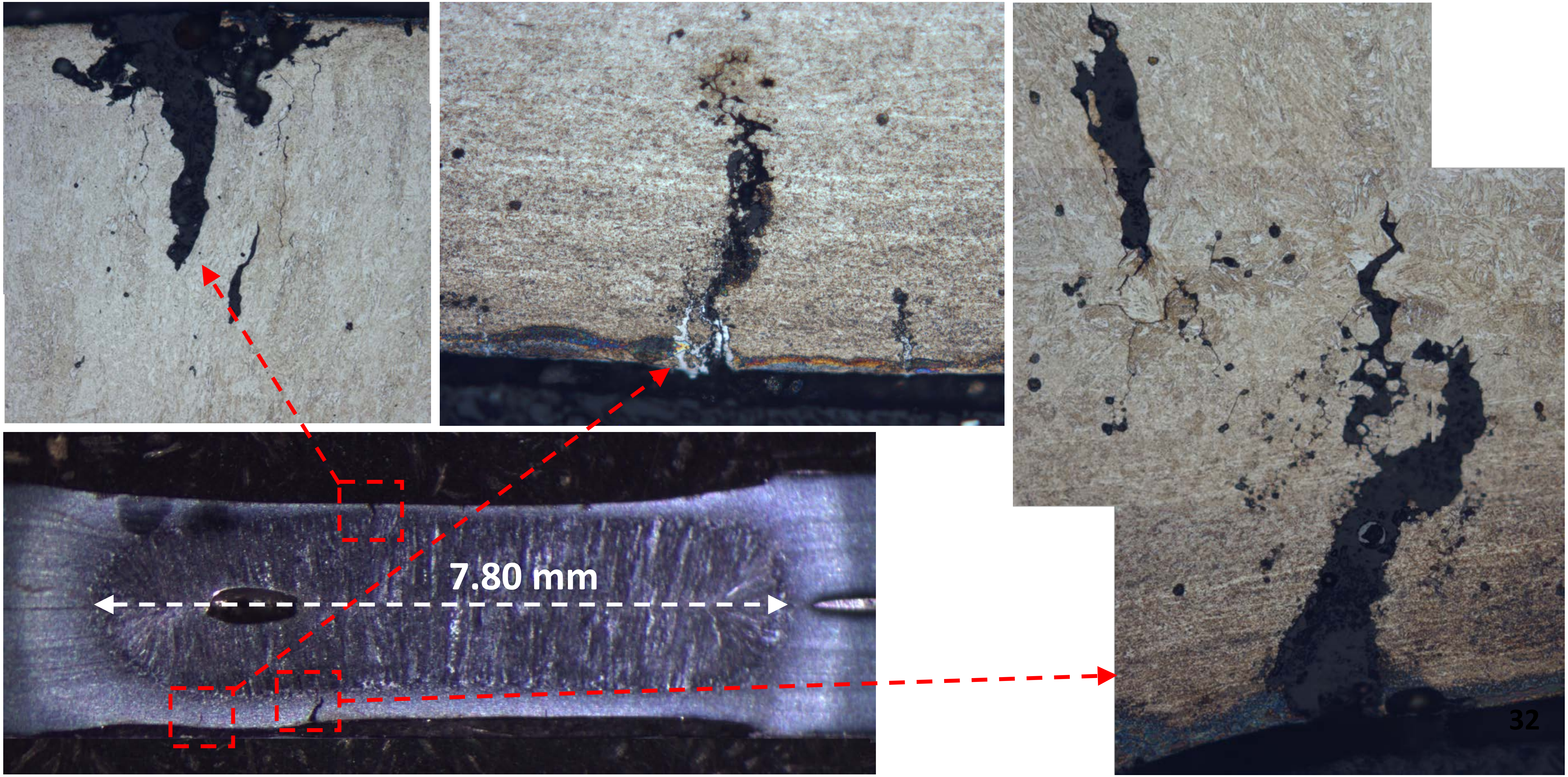
Effect of Weld Current on LME Crack



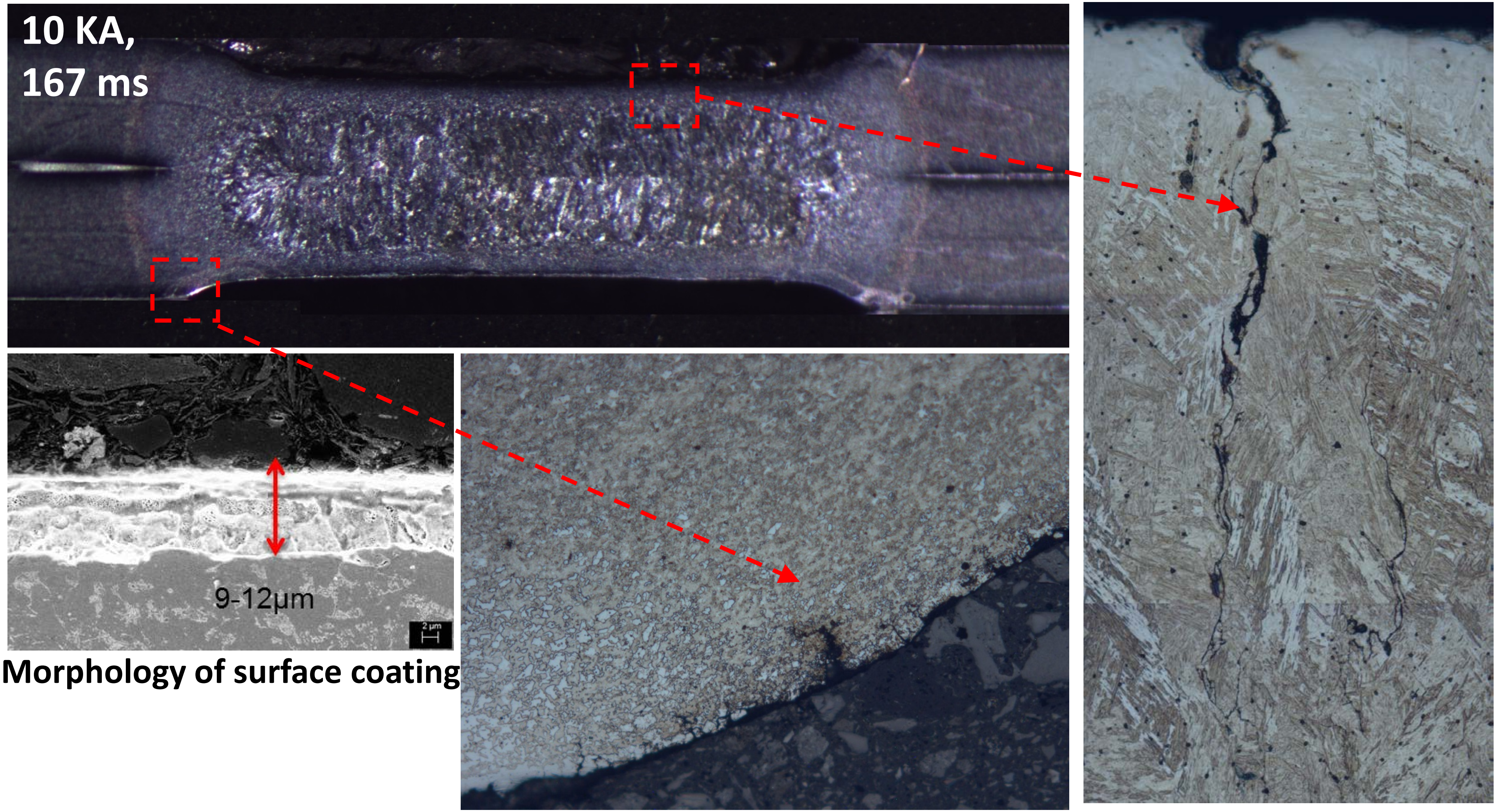


- Higher the welding current larger the LME crack.

GI - Coated Medium Mn Steel at 12.0 kA

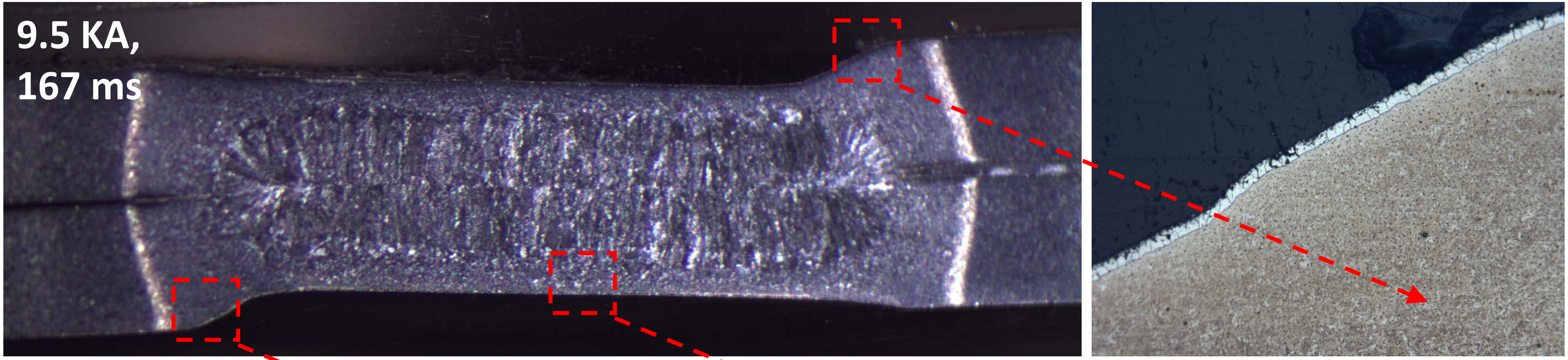


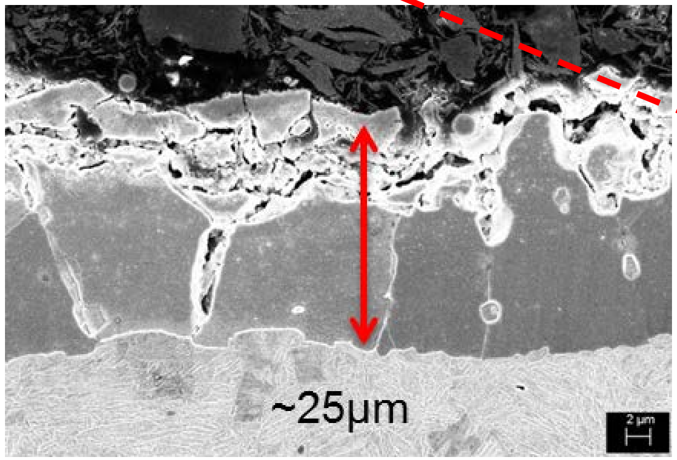
GA - Coated 22MnB5 (As-received Condition)



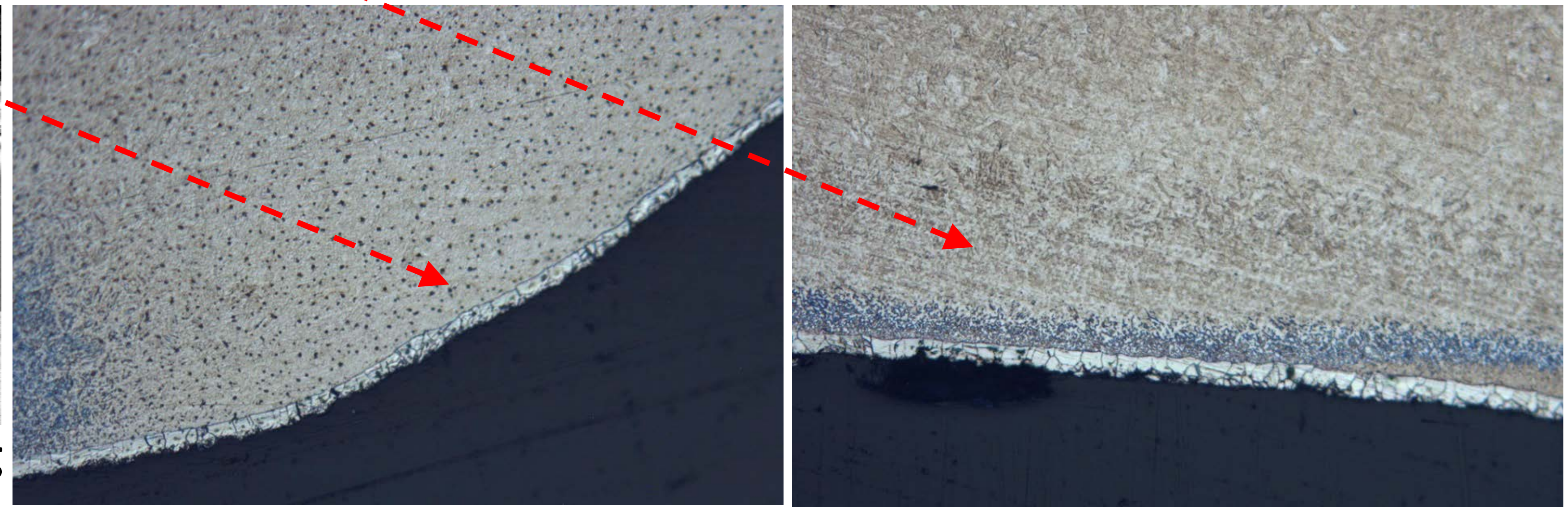
Morphology of surface coating

GA - Coated 22MnB5 (Press-hardened Condition)





Morphology of surface coating

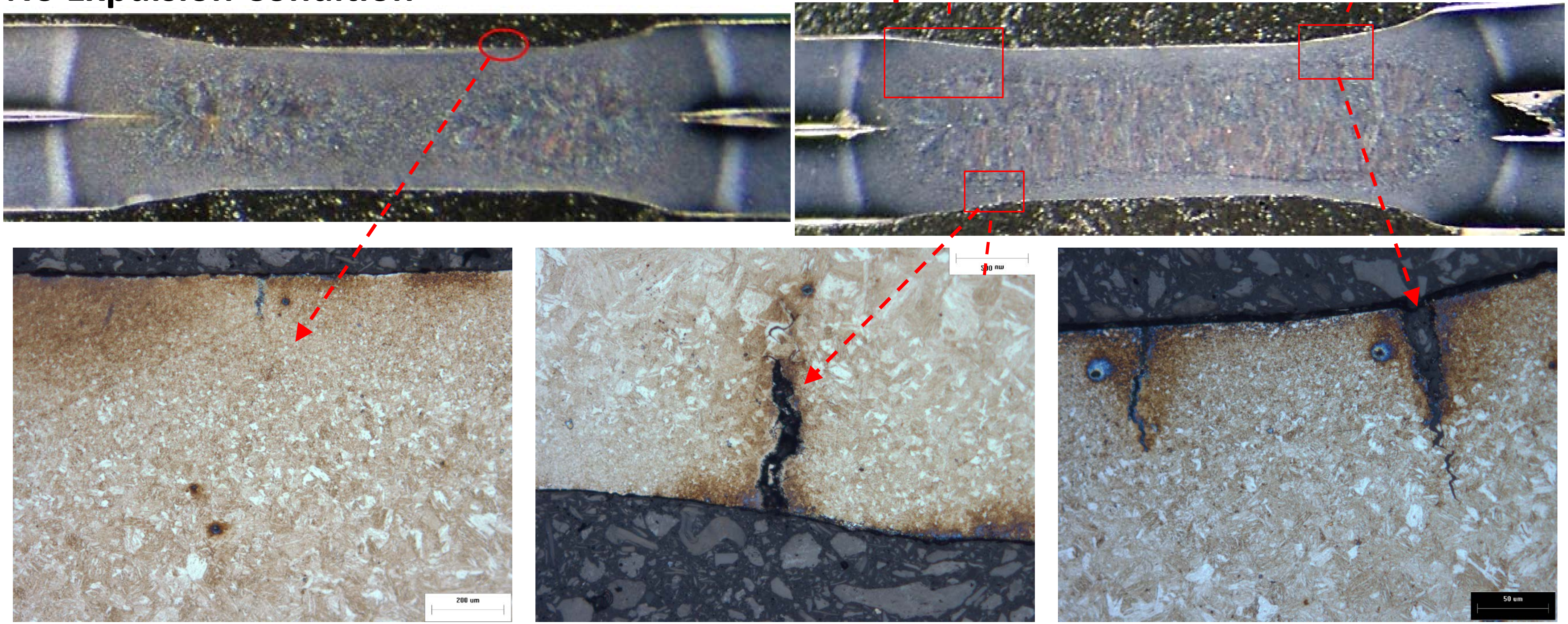


No LME cracks were found in any welding conditions

GI - Coated DP980 Steel

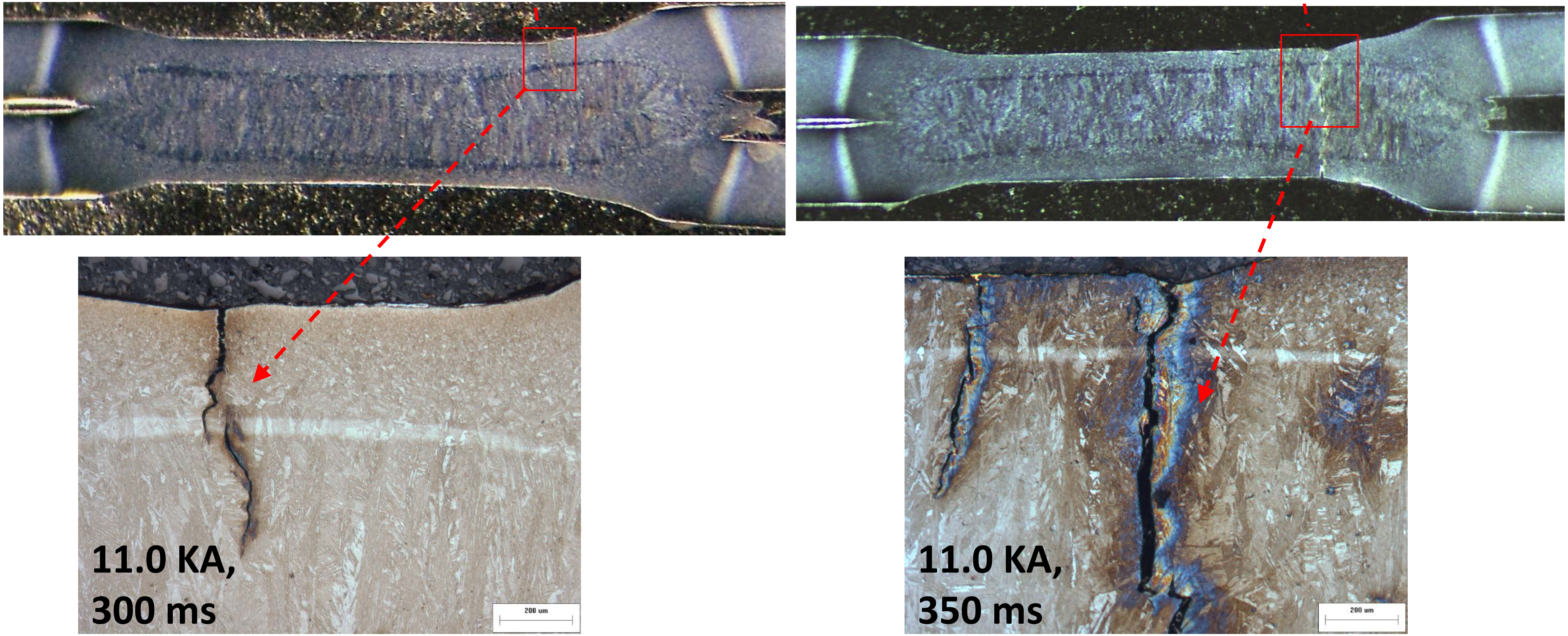
No Expulsion Condition

At Expulsion Condition



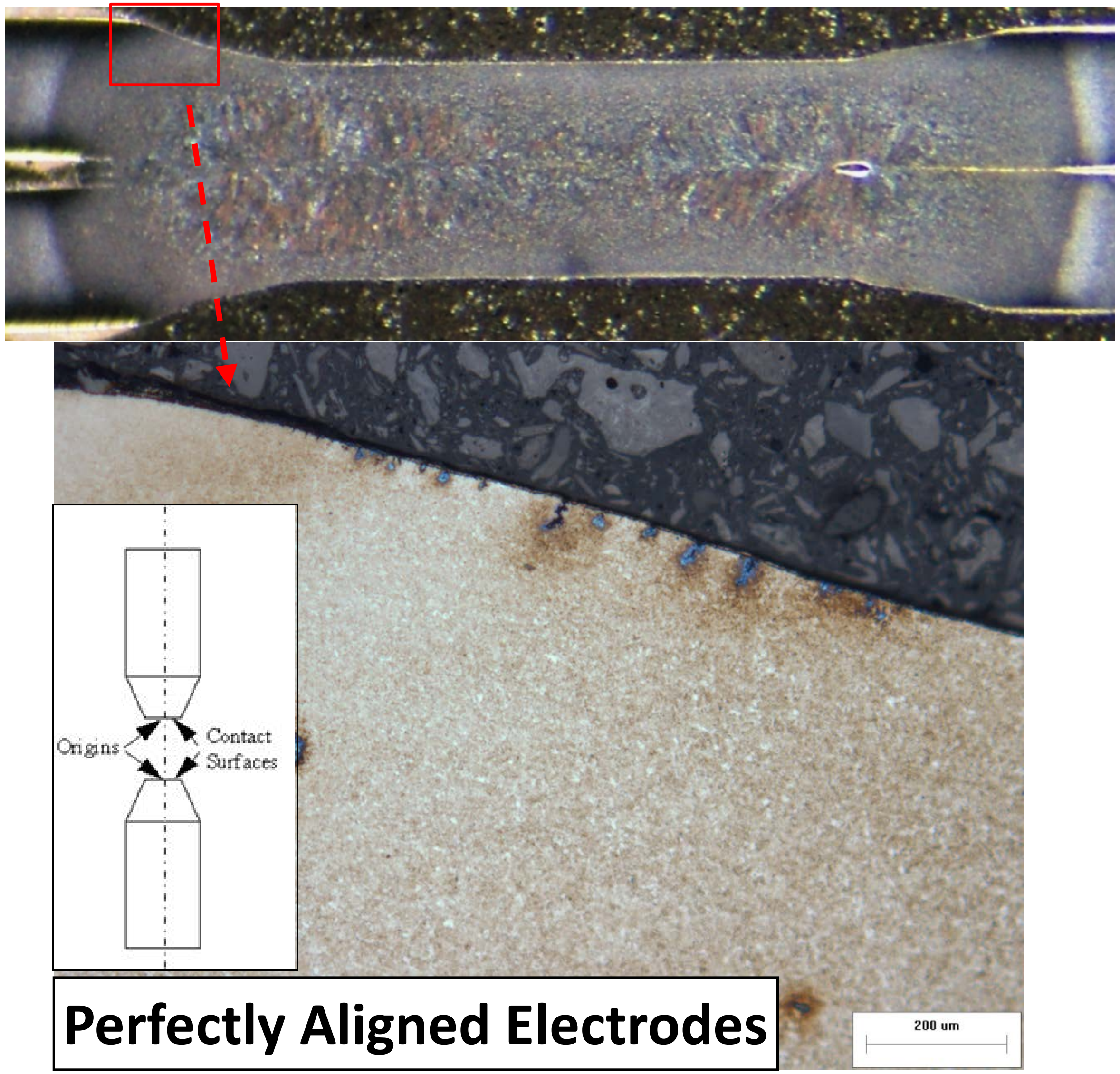
- The GI coated DP980 steels have more tendency to LME cracking.
- LME cracks were found on the sample without and with the expulsion condition.

GA - Coated DP980 Steel

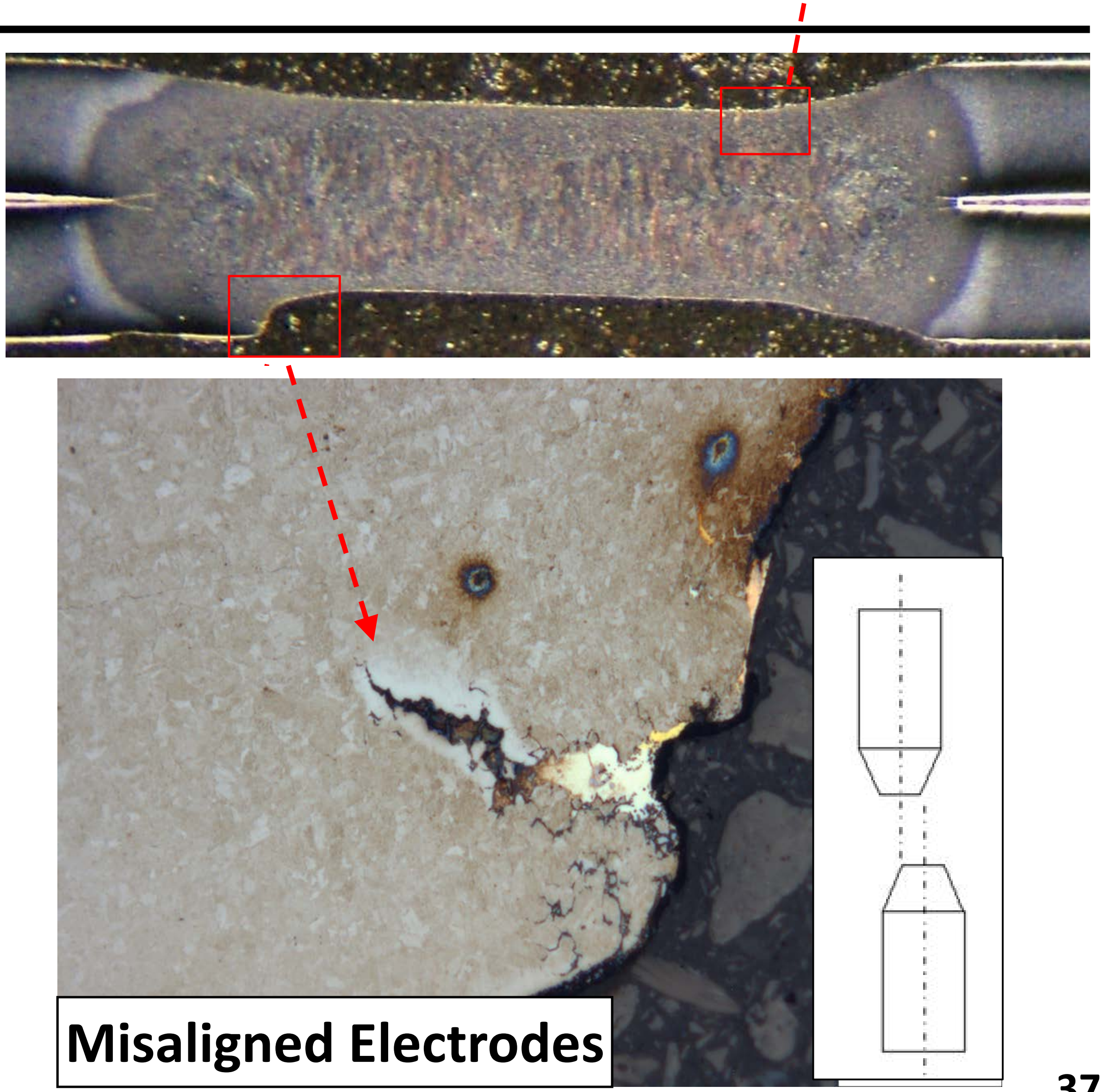


- The GA coated DP980 steels are more resistant to LME cracking.
- LME cracks were not found on the sample without the expulsion condition.
- Heavy expulsion or electrode indentation on the sheet surface is required to generate a visible LME crack

Effect of Electrode Misalignment

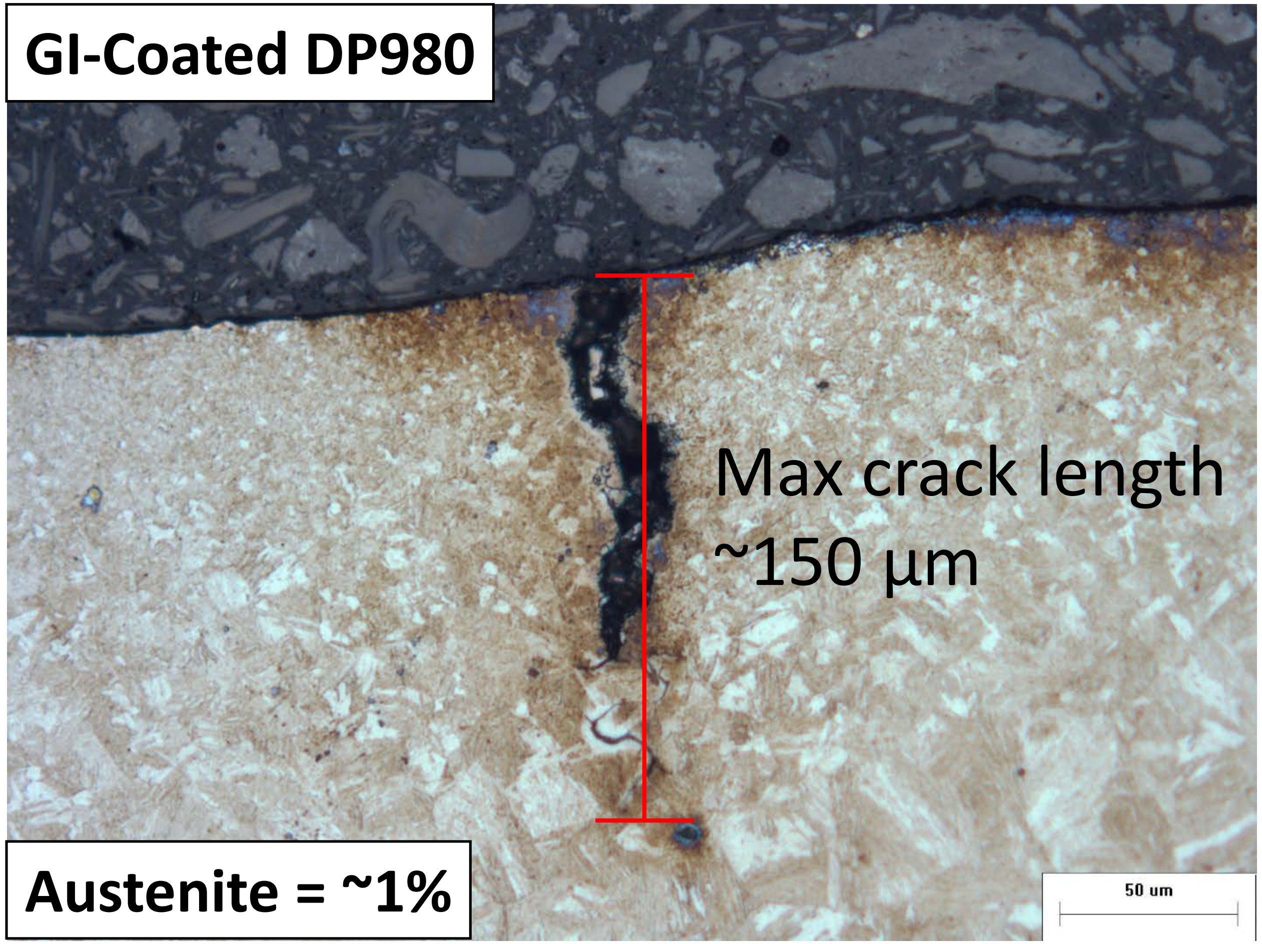


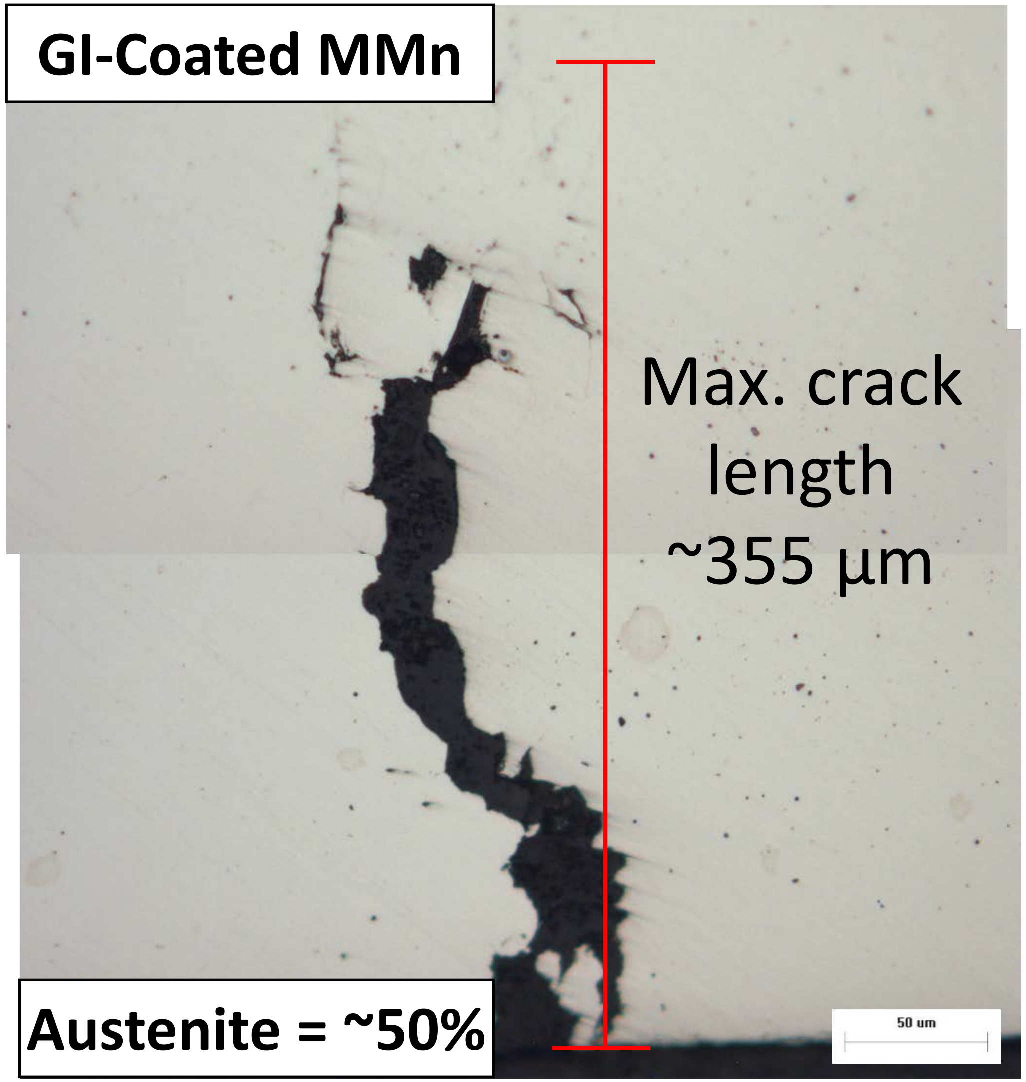
Perfectly Aligned Electrodes



Misaligned Electrodes

Effect of Microstructure –Austenite Fraction





- Considered the samples with the same nugget diameter (7.80 mm)

Summary on Preliminary Work on LME

- **LME cracks were observed in all materials and coating combinations** except GA coated 22MnB5 samples welded as press-hardened condition.
- The GI-coated **50% austenite phase containing MMn steel provides severe LME cracks**. Cracks were found on all welds as nugget diameter exceeds 7.0 mm.
- **The effect of welding current is stronger than the effect of welding time** in generating cracks for both GI and GA coated specimens.
- A large LME cracks on the GA coated samples are associated with the large electrode indentation resulting from expulsion. On the other hand, **visible cracks were observed on the GI coated samples in both expulsion and non-expulsion condition.**
- **Misaligned electrode produces larger LME cracks** by intensifying the local stress during RSW.

Proposal for Future Work

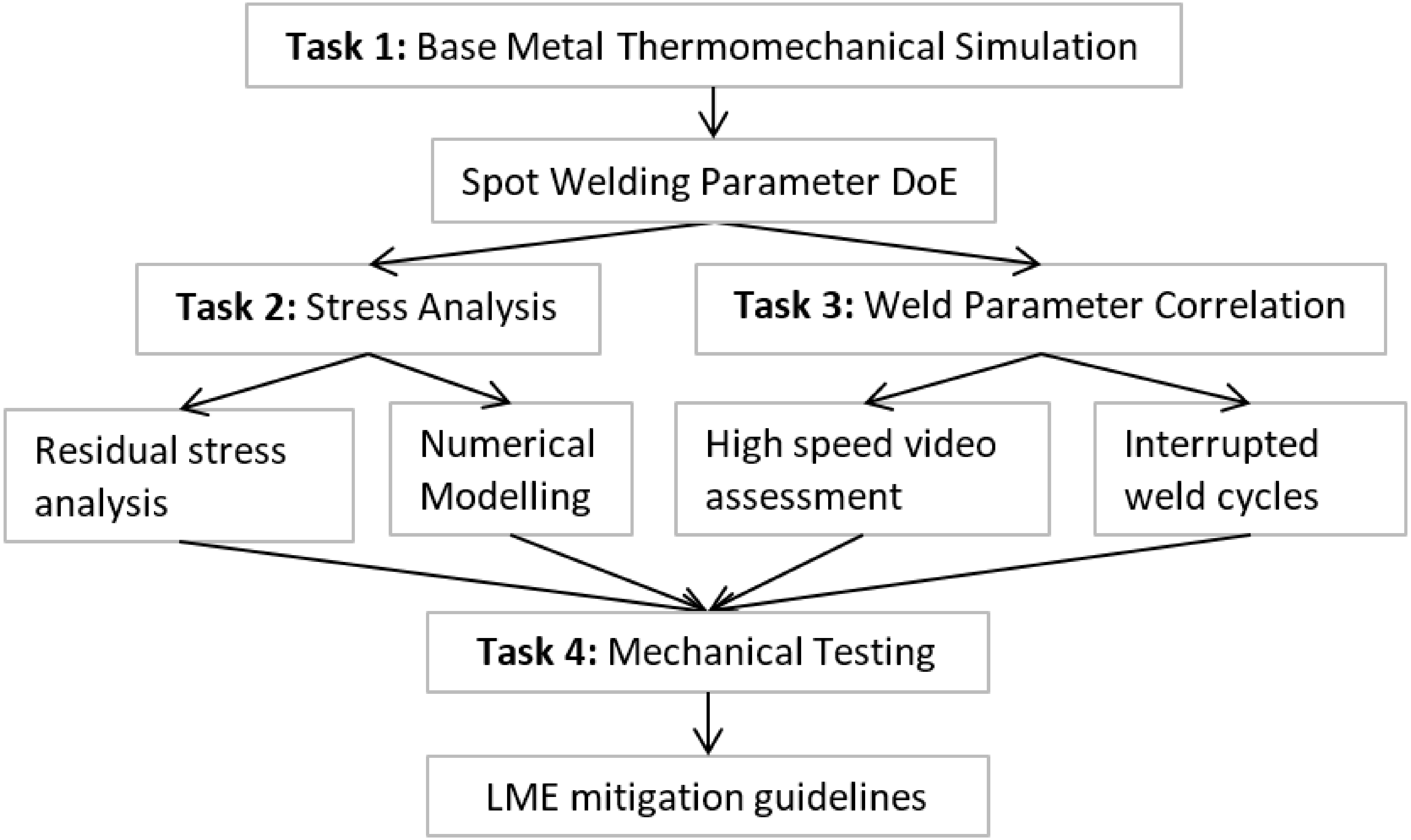
- Task 1 – LME Susceptibility Characterization of Zinc coated Advanced High Strength Steels

- Task 2: Constitutive analysis of induced strain fields during resistance spot welding

- Task 3: Effect of welding parameters on liquid metal embrittlement of spot welds in AHSS

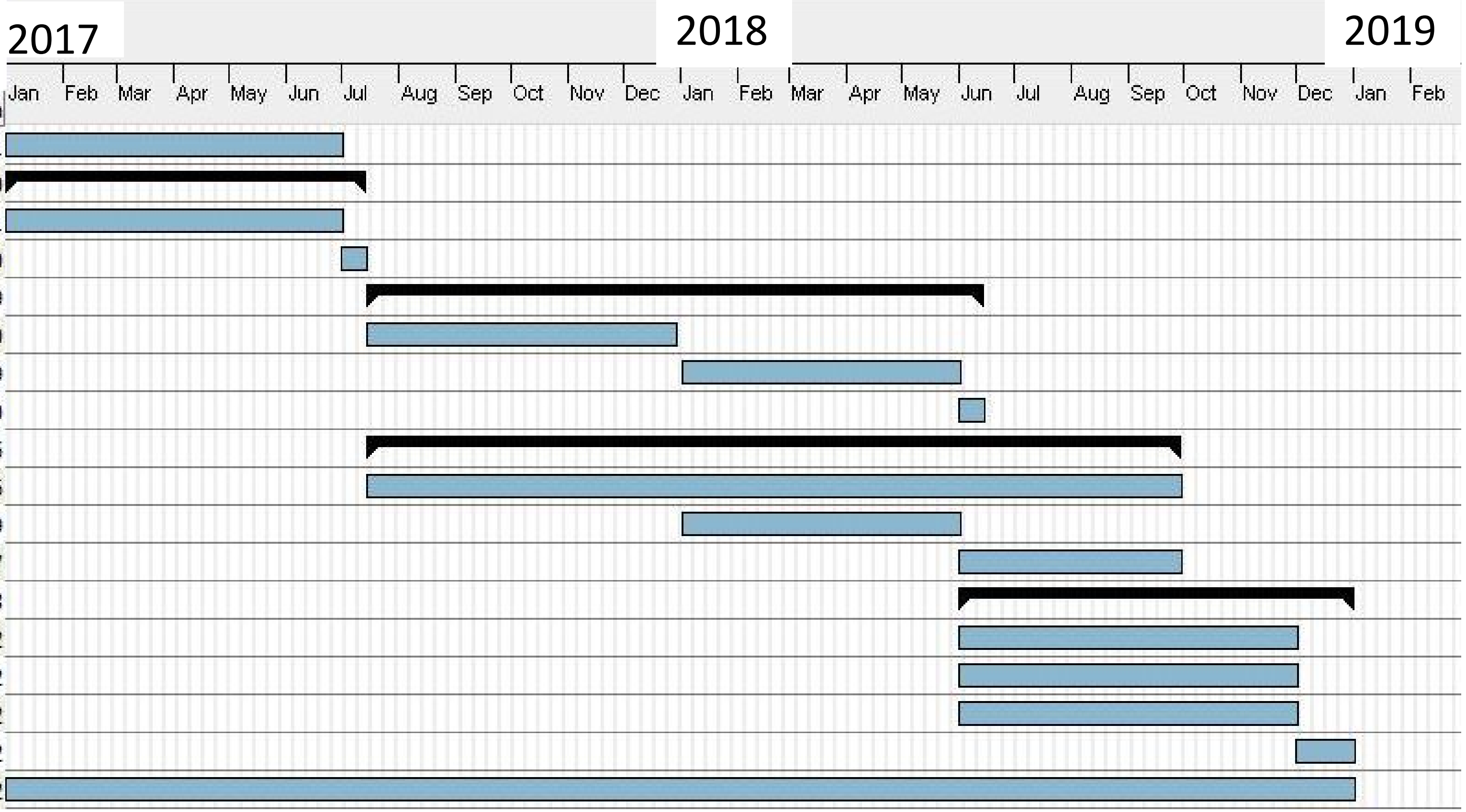
- Task 4: Mechanical performance evaluation of AHSS spot welds

Proposed Research Methodology



Work Plan

Name	Begin date	End date	Duration
Material Procurement	01/01/16	01/07/16	131
Task 1: Thermomechanical Simulation	01/01/16	14/07/16	140
Hot Tensile Testing	01/01/16	01/07/16	131
Interim Report #1	01/07/16	14/07/16	10
Task 2: Stress Analysis	15/07/16	14/06/17	239
Numerical Modelling	15/07/16	29/12/16	120
Resdiual Stress Analysis	02/01/17	01/06/17	109
Interim Report #2	01/06/17	14/06/17	10
Task 3: Weld Parameter Correlation	15/07/16	29/09/17	316
Weld Parameter Trials	15/07/16	29/09/17	316
High Speed Camera Visualization	02/01/17	01/06/17	109
Interrupted Weld Cycle Trials	01/06/17	29/09/17	87
Task 4: Mechanical Performance Evaluation	01/06/17	01/01/18	153
Tensile Shear Testing	01/06/17	01/12/17	132
Cross Tension Testing	01/06/17	01/12/17	132
Fatigue Testing	01/06/17	01/12/17	132
Final Report	01/12/17	01/01/18	22
Metallography and Characterization	01/01/16	01/01/18	522



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- Dr. Joe McDermid for undertaking ICP-MS coating analysis at **McMaster University**

Thank you
for your attention!

Further Questions – Contact:

Prof. Norman Zhou
University of Waterloo,
200 University Avenue West,
Waterloo, ON, N2L 3G1
Email: nzhou@uwaterloo.ca