American Iron and Steel Institute

Liquid Metal Embrittlement A/SP Research Results Webinar

RAPID EVALUATION PROCEDURES

JULY 28, 2020

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Liquid Metal Embrittlement A/SP Research Results Webinar

Introduction: John Catterall

Vice President, Automotive Program

American Iron and Steel Institute

Liquid Metal Embrittlement
A/SP Research Results Webinar

Presenter: Michael Karagoulis, PhD
Master Mechanic - Weld Development, Global ME
Body-in-White
General Motors Corporation

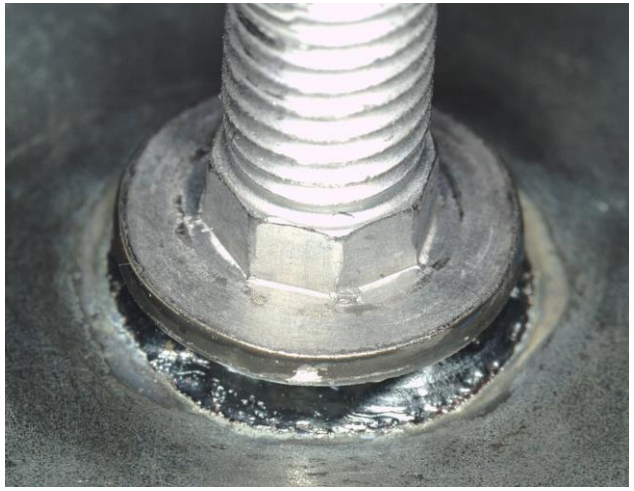
Auto/Steel Partnership

Examples of LME Cracking in Automotive Welds

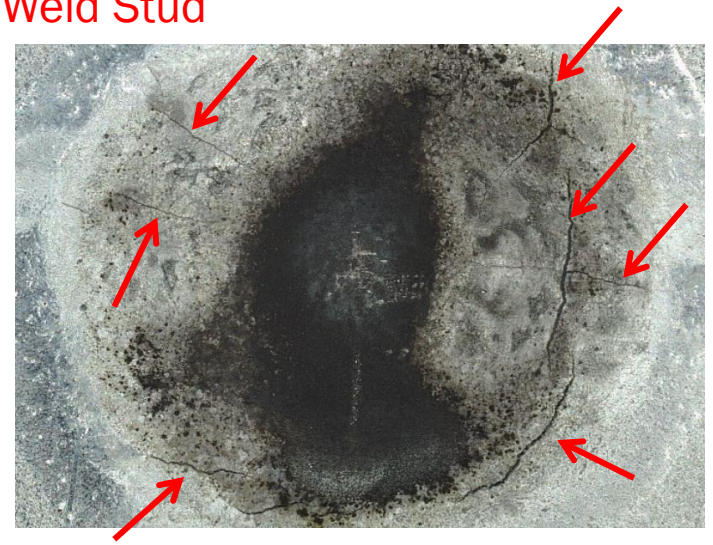
Resistance Spot Weld

Gas Metal Arc Weld (GMAW)

Drawn Arc Weld Stud



Top View

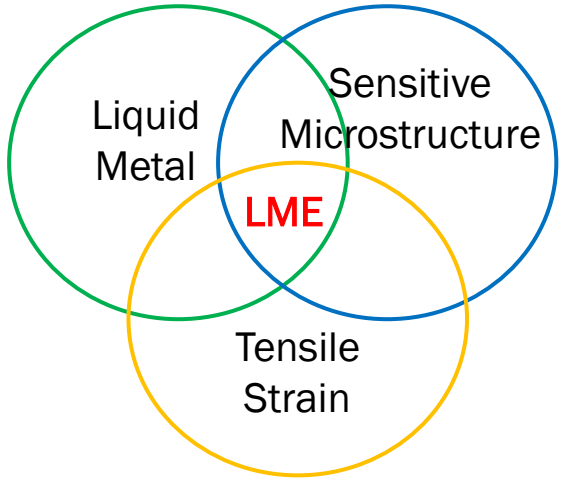


Bottom View

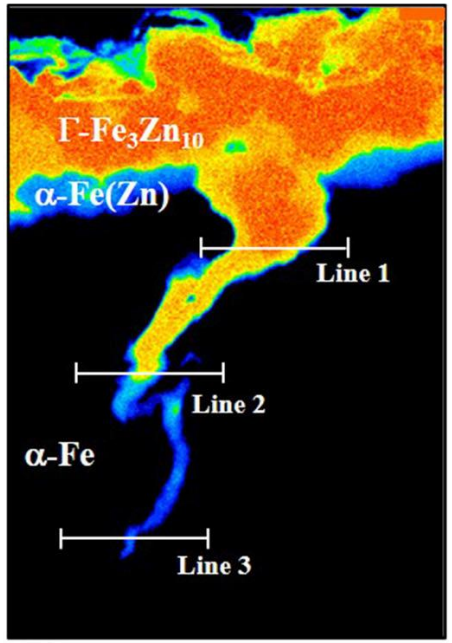
What Causes LME? (liquid metal embrittlement)

LME is the instantaneous, preferential dissolution of steel grain boundaries, due to the simultaneous action of tensile strain, a foreign liquid metal, and a susceptible microstructure.

LME cracking occurs when 3 specific enabling factors are all switched ON:

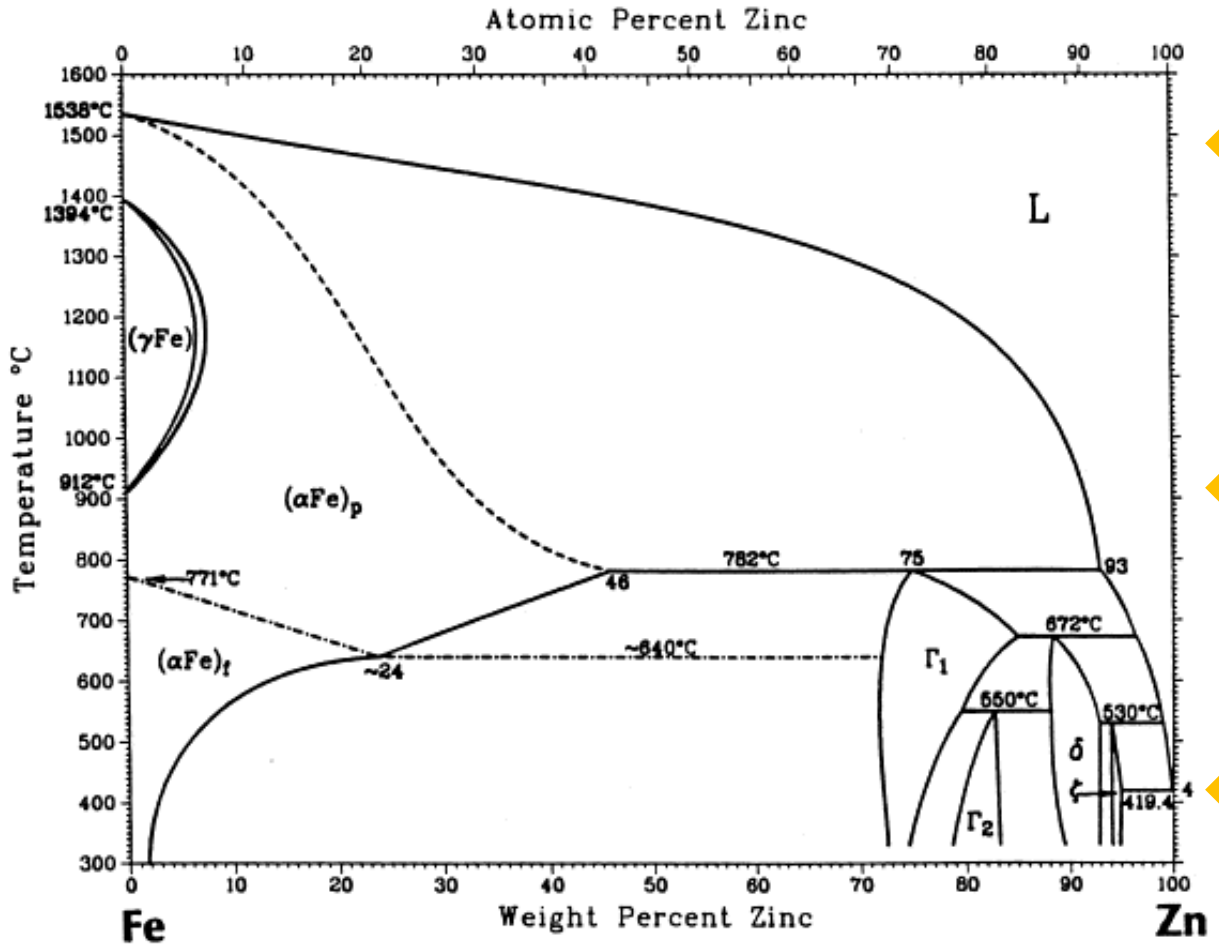


LME occurs by sudden, deep zinc penetration into the steel grain boundaries.



Kang, Cho, Lee, DeCooman 2016

Some Quick Metallurgy…



General melting point of steels ~1500C (2700F)

General boiling point of zinc coating 900C (1650F)

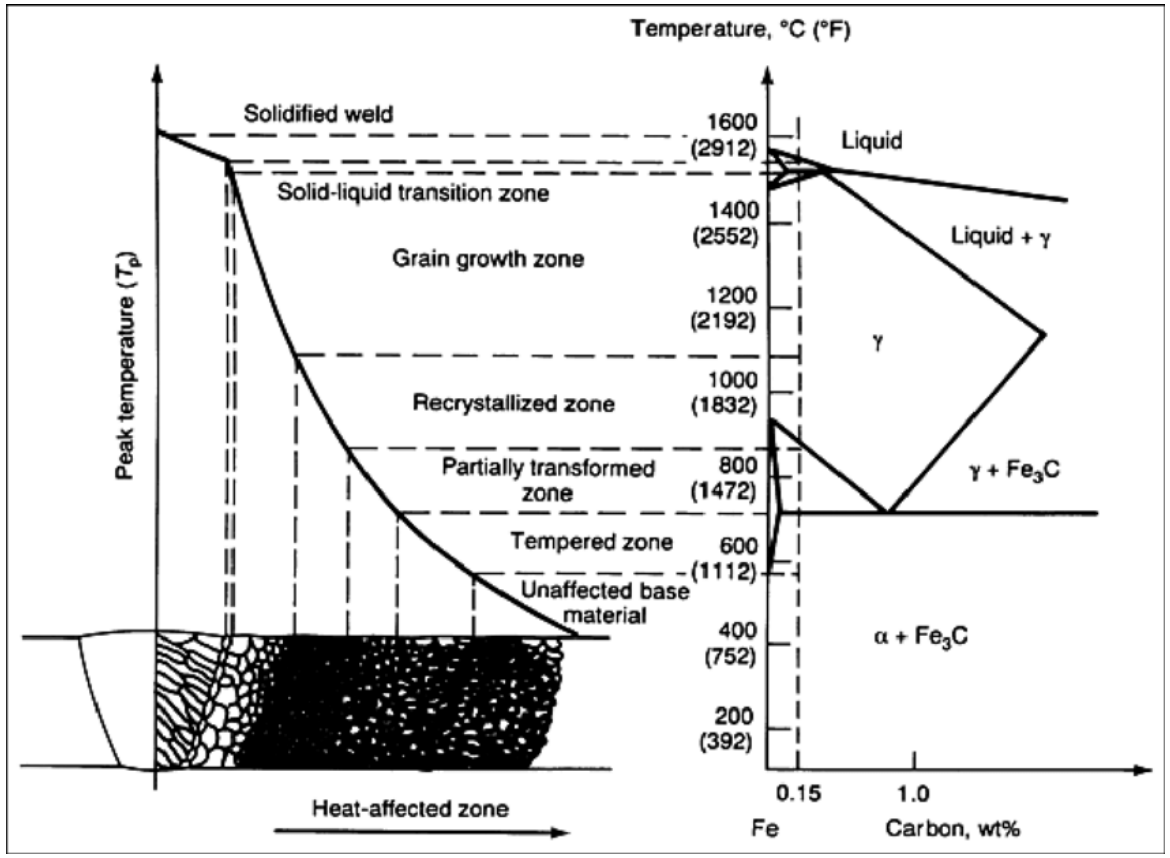
Expected temperature range of LME

General melting point of zinc coating 420C (790F)

T.B Massalski, Phase Diagrams. ASM Metals Handbook, 3 (1992), p. 206

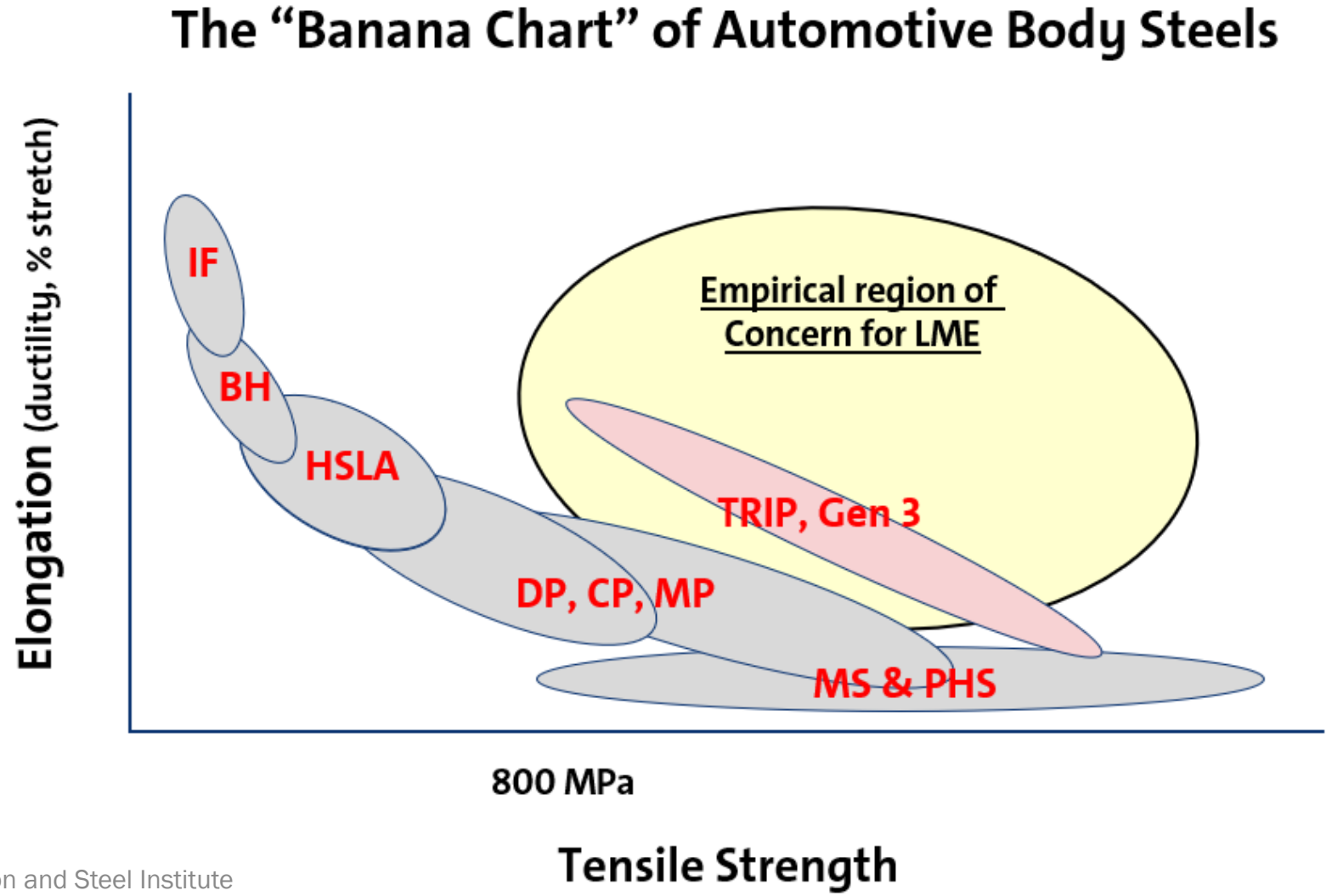
Why the Sudden Interest in LME by Auto Industry?

Unfortunately, for most steel welding, 400 – 900C is unavoidable within the temperature range of the Heat-Affected Zone (HAZ)



Aucott, Lee. (2015). Mechanism of solidification cracking during welding of high strength steels for subsea linepipe.

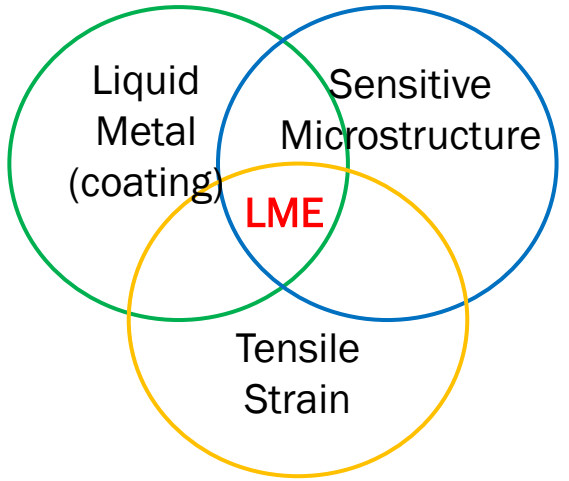
Not All Galvanized Steels are Susceptible to LME



A Practical Problem-Solving Strategy for LME:

1. Figure out how to reliably Turn On LME
   - Develop laboratory procedure(s) which will activate LME according to the Venn Diagram
   - Characterize specific combinations of Coating, Temperature, Strain, and Material
   - Establish LME metrics or ratings for steel

2. Figure out how to reliably Turn Off LME
   - Modify chemistry?
   - Modify microstructure?
   - Modify coating?
   - Modify welding?



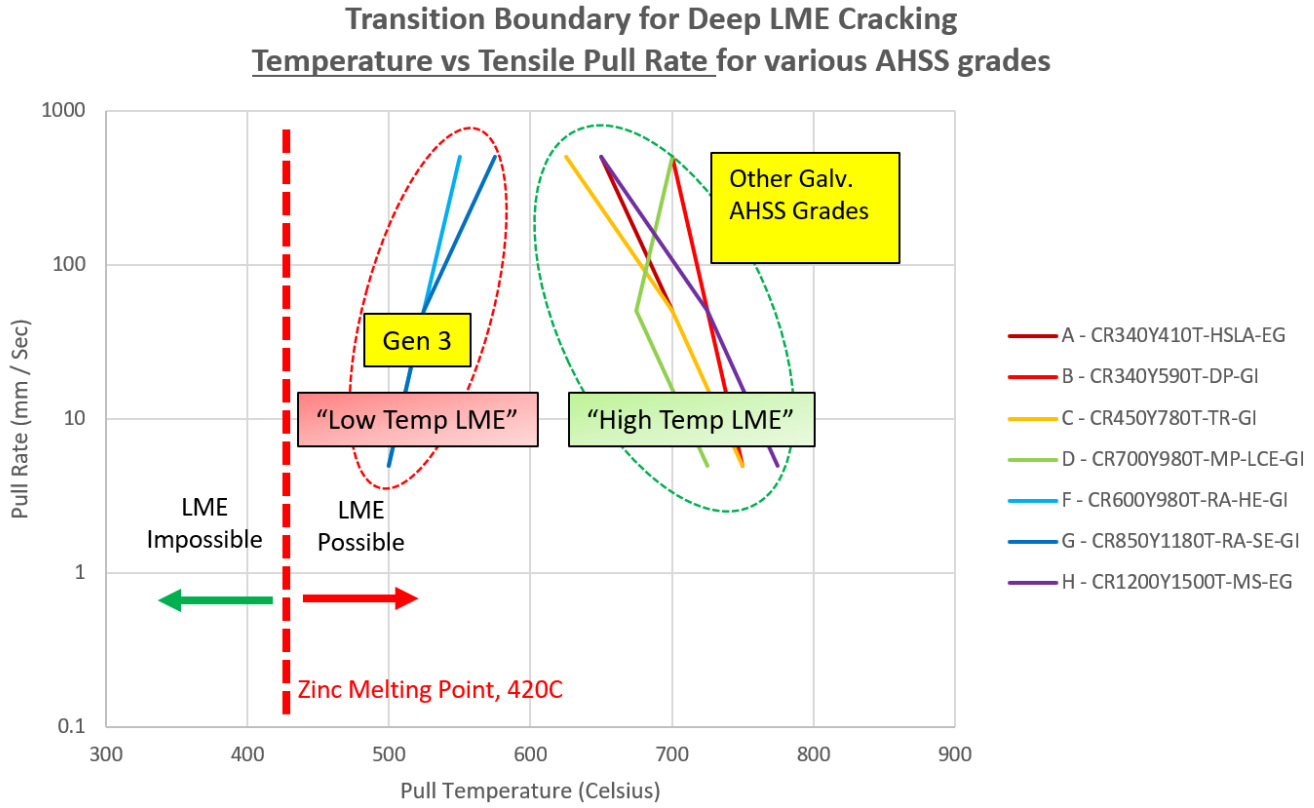
Venn Diagram

Turning On the LME Reaction, using a Gleeble

A/SP Sponsored Gleeble Testing (Hot Tensile Testing) at OSU

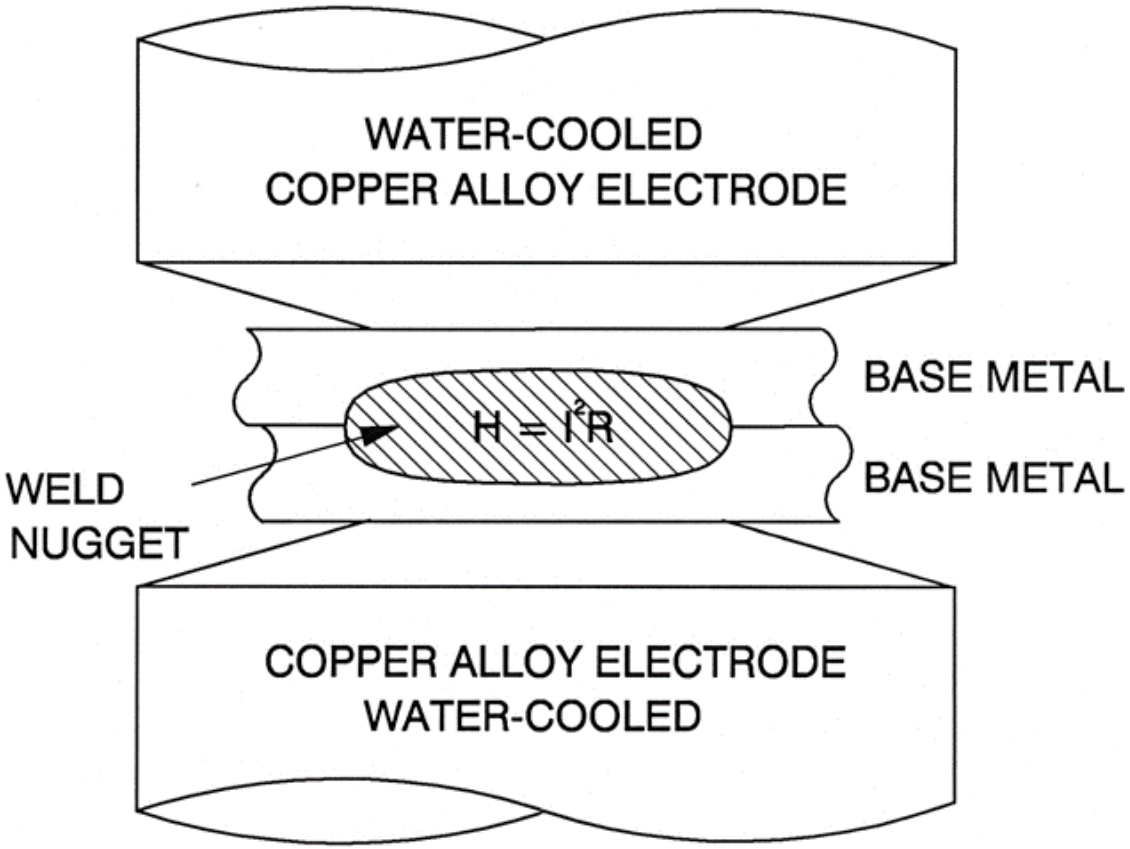
Isolate the LME Cracking Effect away from welding variables

Liquid Metal Embrittlement Cracks



Result: Two kinds of LME in autobody steels were identified: Low Temperature, versus High Temperature

Turning On the LME Reaction, using a Spot Welder



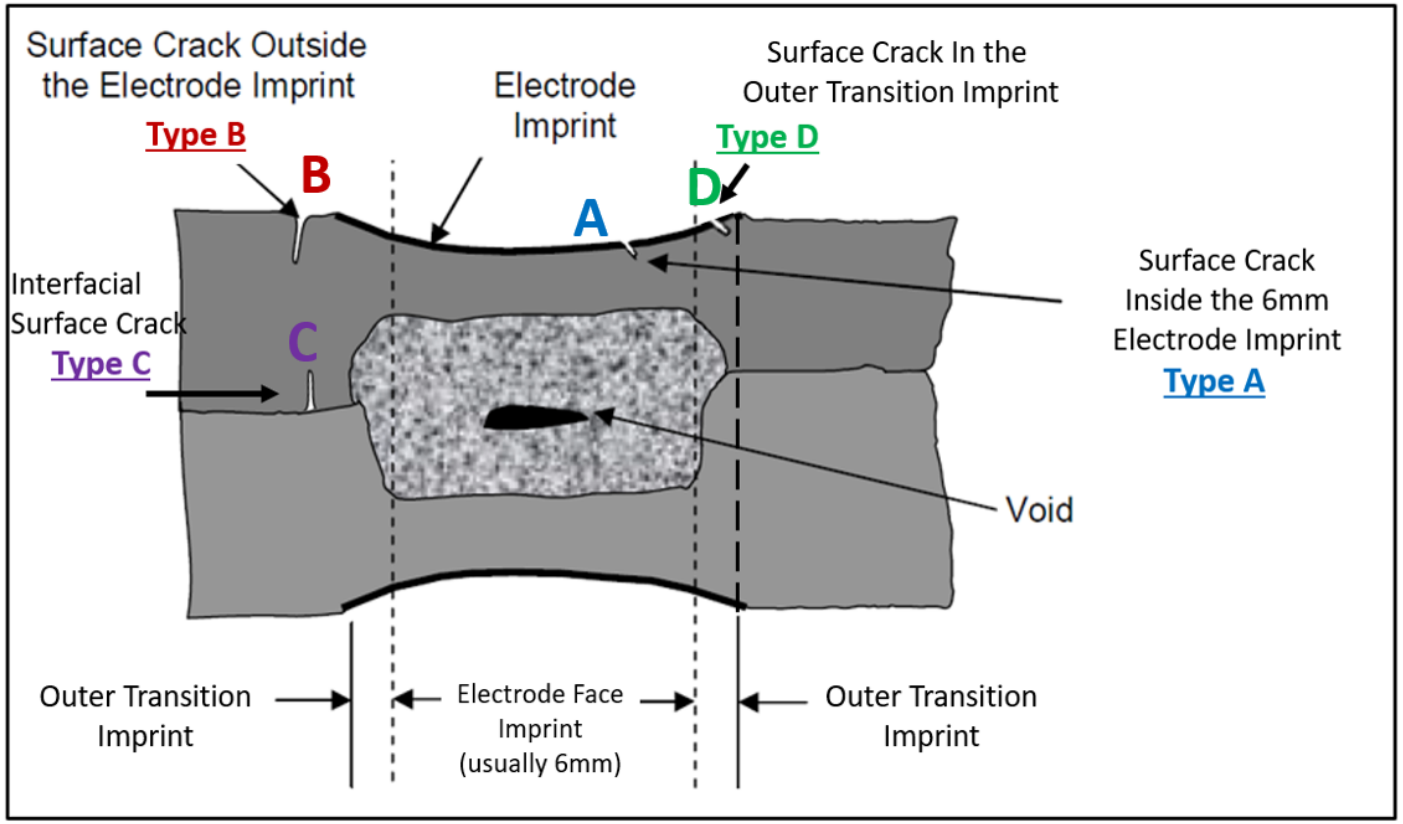
Challenges:

How to create the same Temperature and Strain conditions of the Gleeble machine, using a simple spot weld machine?

1. Creating Tensile Strain using an applied compressive load
2. Creating the LME Activation Temperature at the tensile strain location.
3. Repeatability
   A. Spot welding dynamic variables:
      i. Current density
      ii. Force and pressure on Tip Faces
      iii. Expulsion

LME Cracks Can Occur at Different Weld Regions

Crack Location Map
used for test interpretation



Two Types of LME are Most Prevalent

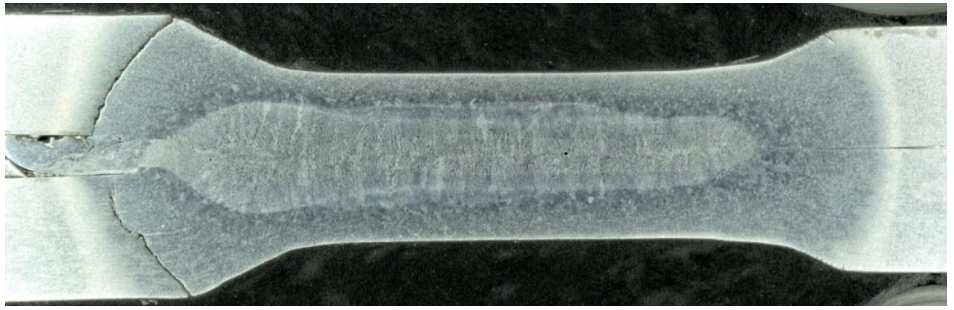
Type A

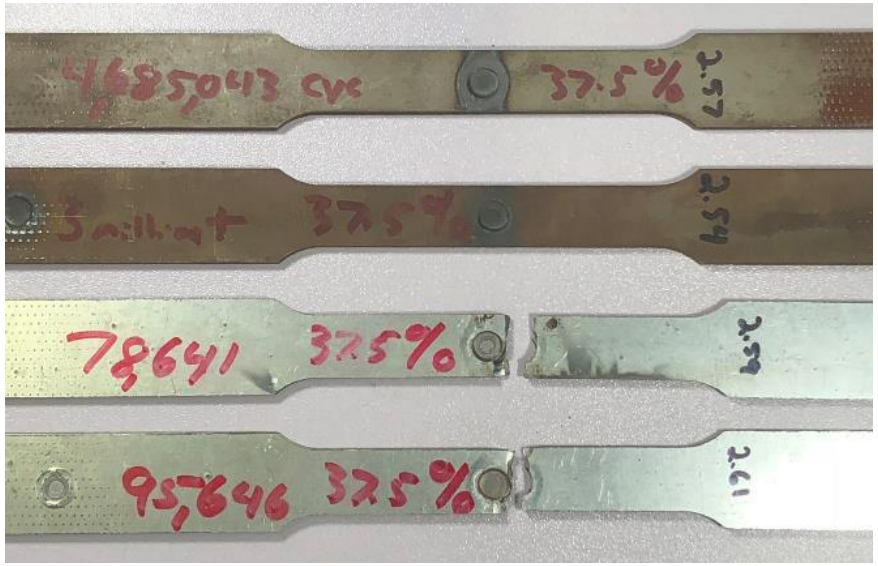
Cracks within Electrode Imprint

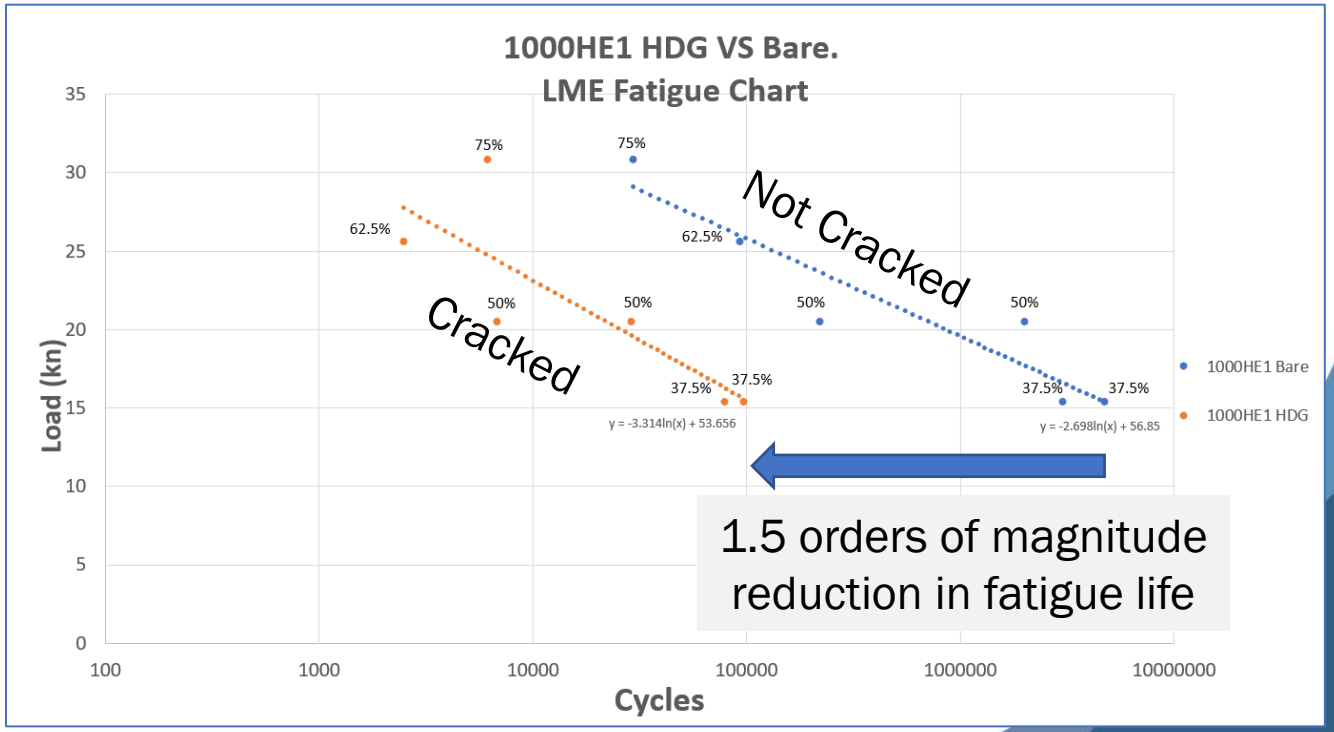
Type B

Cracks around Periphery

But Type B has Been Shown to Degrade Weld Strength the Most

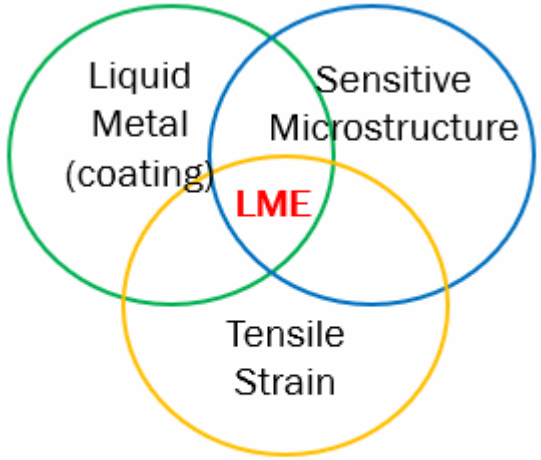






Experimental Strategy to Turn On Type B Cracking

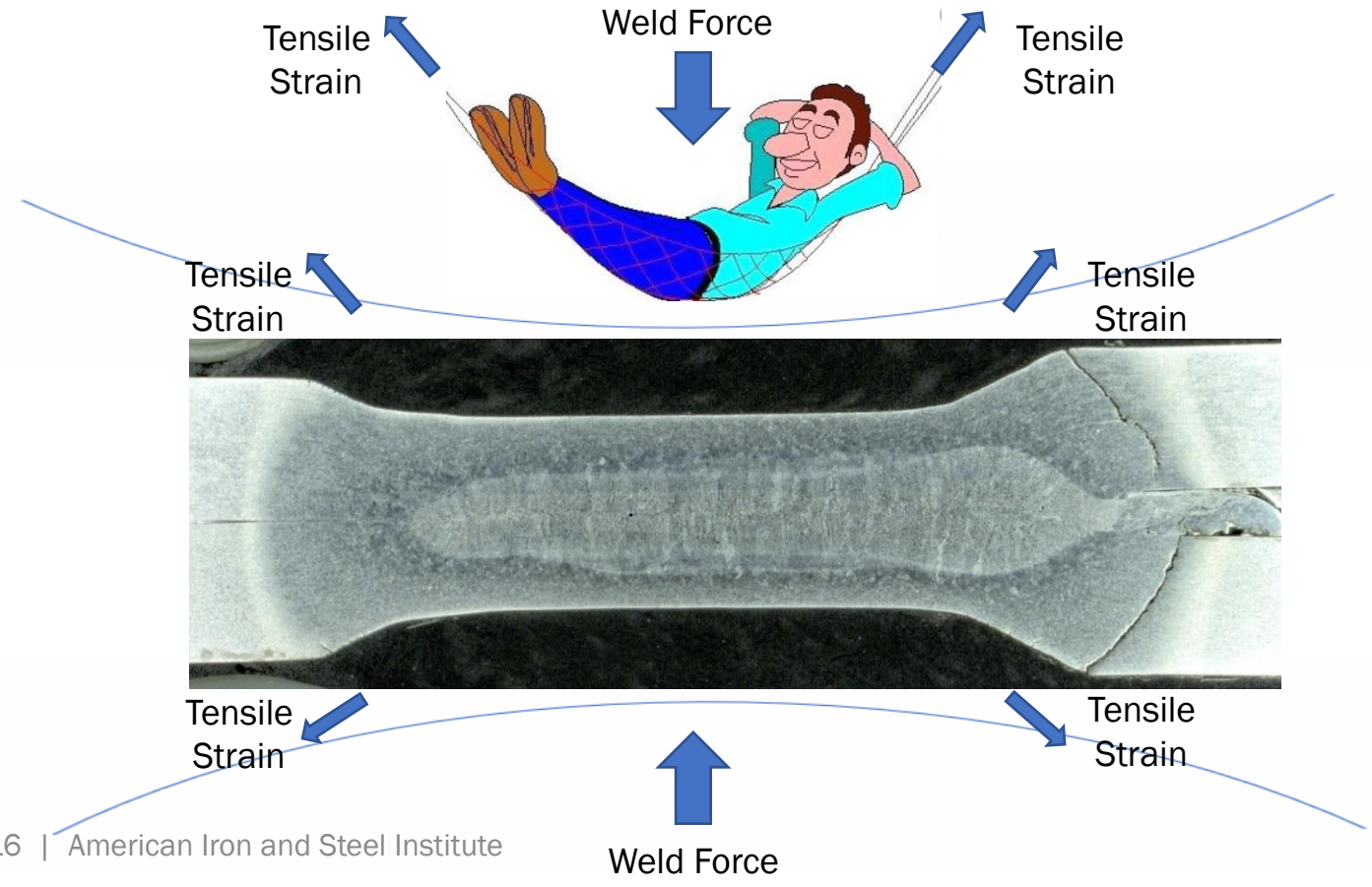
1. Maximize Tensile Strain at Type B Crack Location
2. Control HAZ Temperature at Type B Crack Location
3. Suppress Weld Expulsion



Venn Diagram

1. Designing in Surface Tensile Strains using Applied Compression:

How Tensile Strain occurs during Electrode Indentation
Principle: “Hammock Strain”



Whale Sling

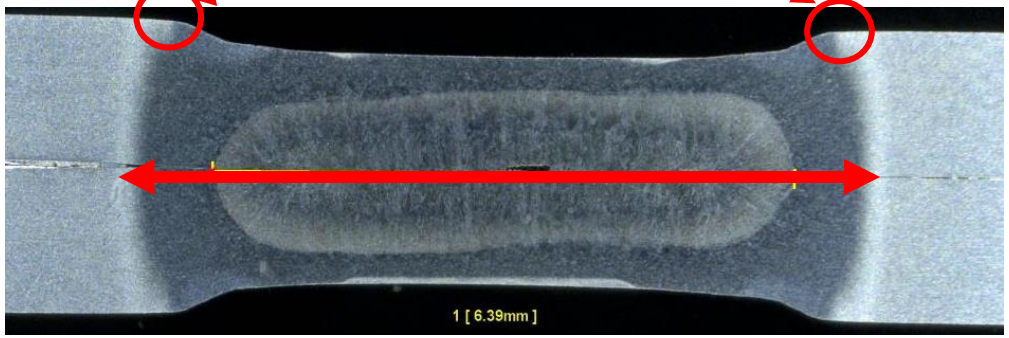
“Free Willy” Movie 1993

The whale sling fabric sees tension, even under compressive weight of the whale.

2. Achieving the "Gleeble Temperature" at the Crack Site Requires Creating a Very Wide Heat Affected Zone

These target crack sites did not reach initiation temperature

Standard GM Weld Time
For 1.6mm Sheet

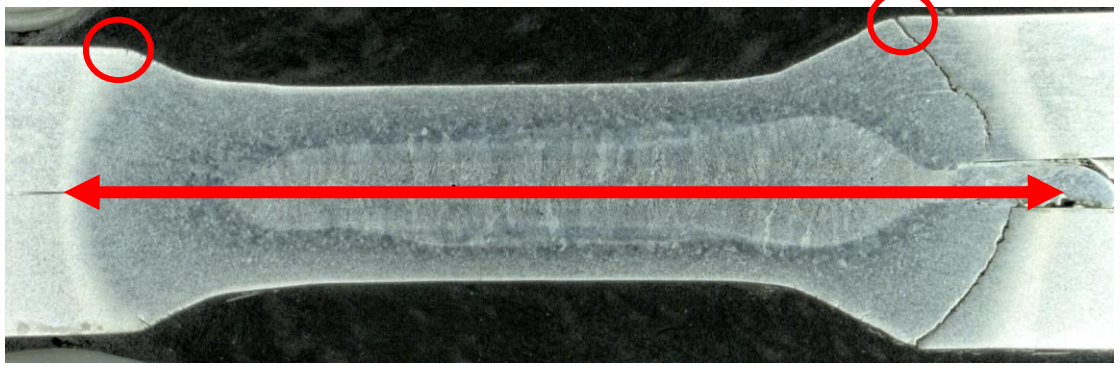


Weld Time = 640ms

HAZ diameter ~ 8.5mm

Type B Crack Site (needs 500 – 600C here to initiate the crack)

"Gleeble-ized"
Weld Time
For 1.6mm Sheet



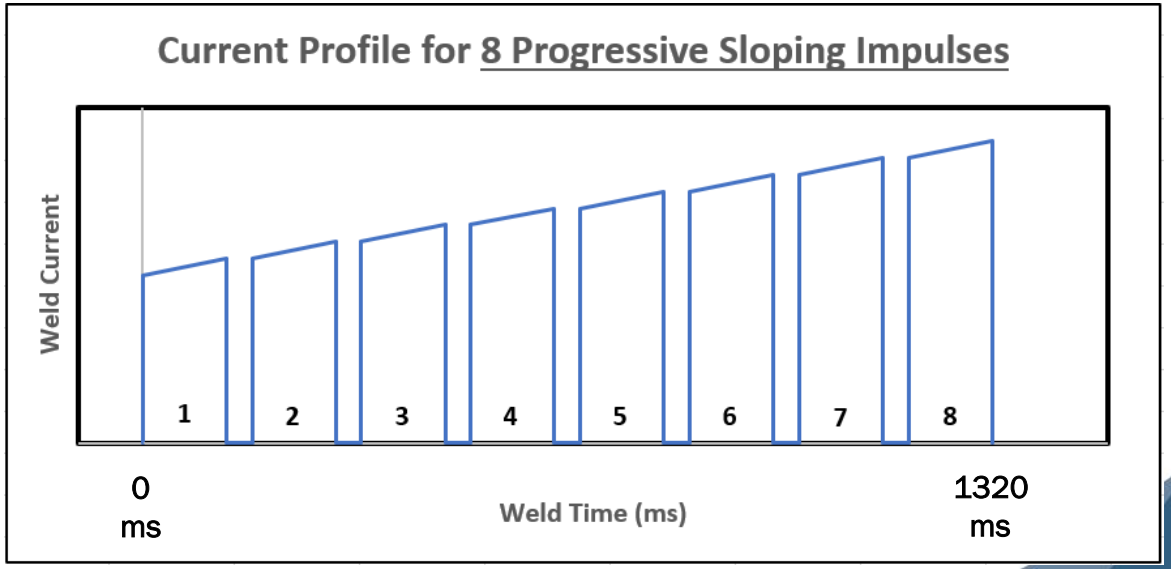
Weld Time = 1320ms

HAZ diameter ~ 10.7mm

3. Improving Test Repeatability Requires Suppression of Weld Expulsion.

Lengthening weld time naturally increases the expulsion tendency of weld metal.
Expulsion causes scatter in LME results, due to the chaotic disturbance of expulsion on momentary weld force and power.
For repeatable LME cracking, expulsion must be suppressed as long as possible.

The most effective way to suppress expulsion in this case is to program the welder with **Progressive Sloping Impulses**.



RESULTS

A Tale of Two Steels:

3rd Gen 980 (RA) Hot Dip Galvanized Steels (GI) with high elongation (HE)

Steel “F”

1.4 mm CR980T-600Y-RA-HE-GI

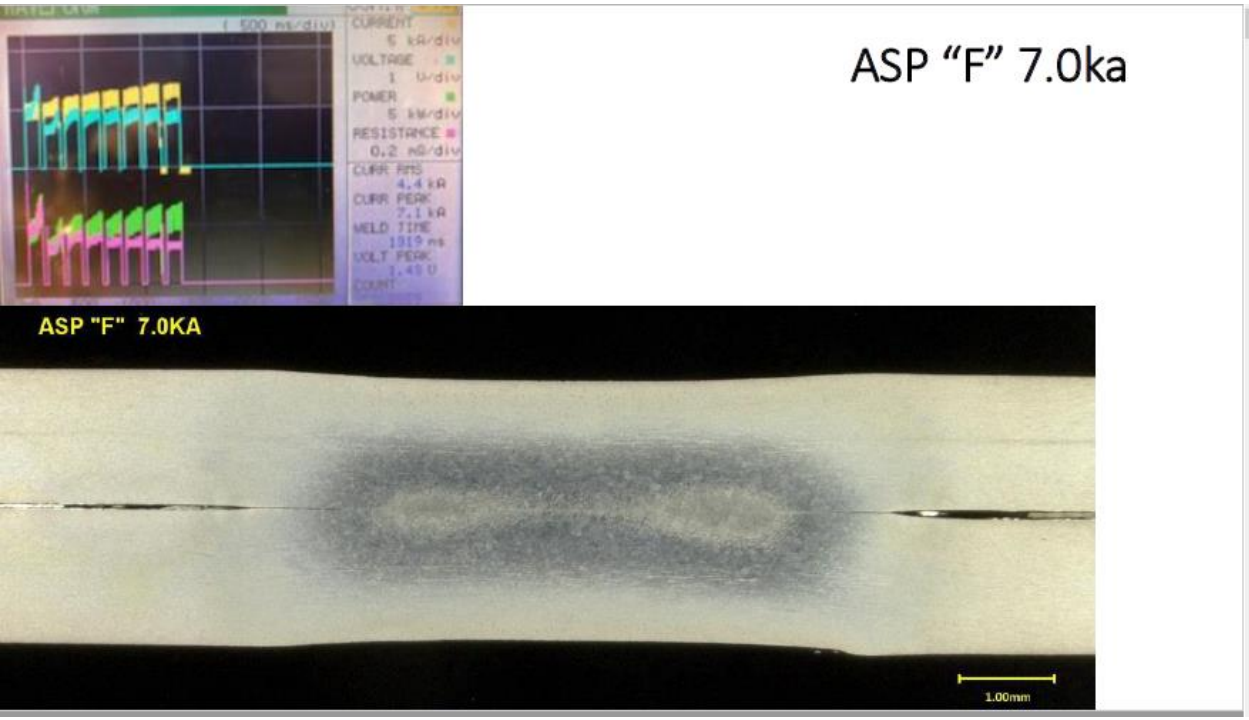
Steel Lot #154

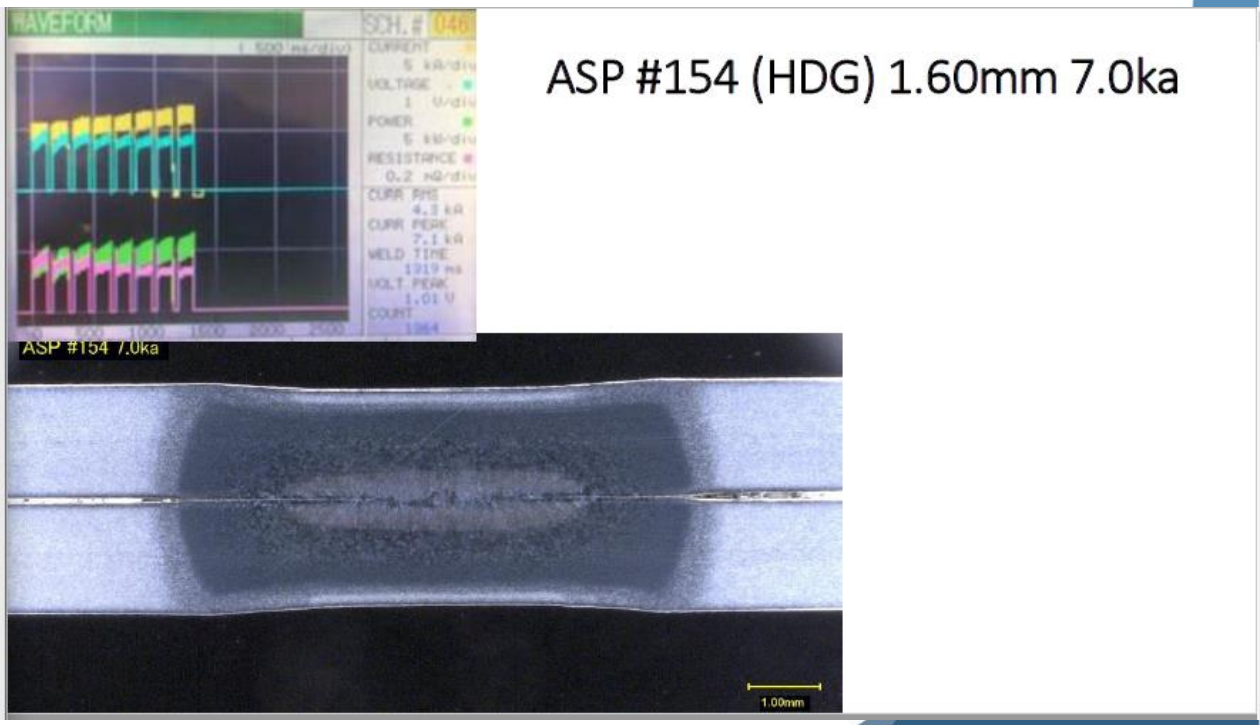
1.6 mm CR980T-600Y-RA-HE-GI

Test Results for Bad and Good Steels

Steel “F”
CR980T-600Y-RA-HE-GI
1.4mm

Steel Lot #154
CR980T-600Y-RA-HE-GI
1.6mm





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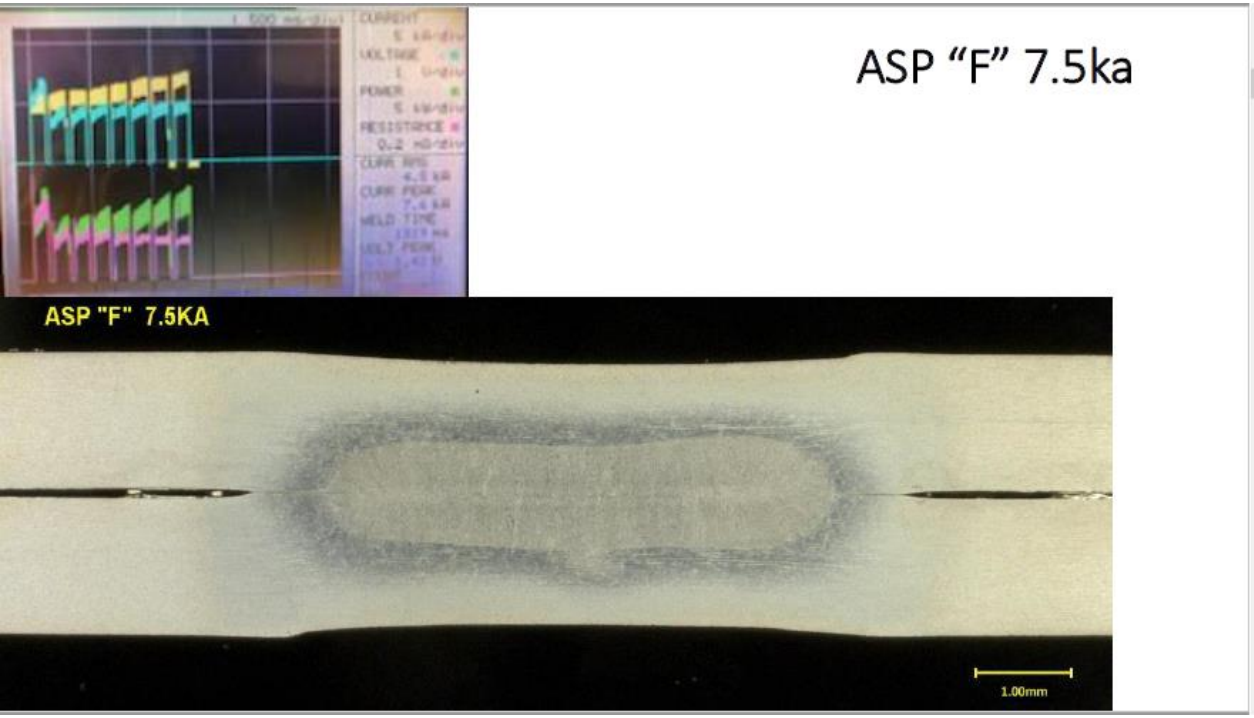

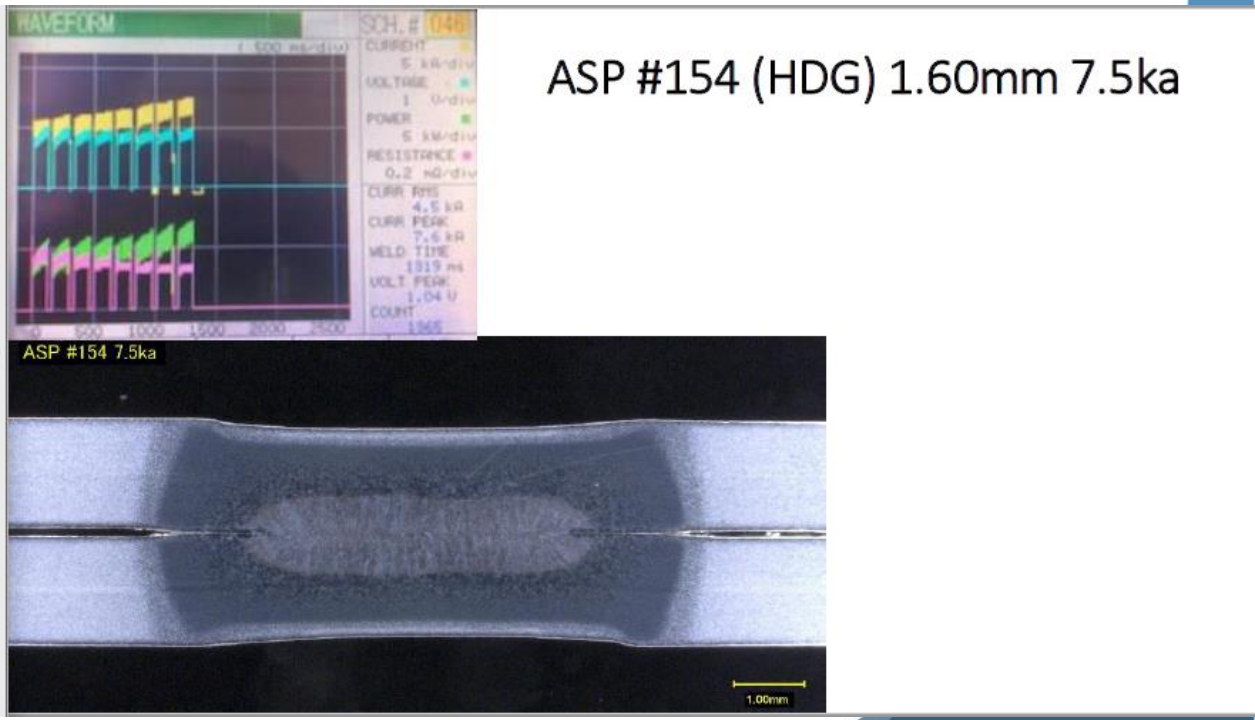

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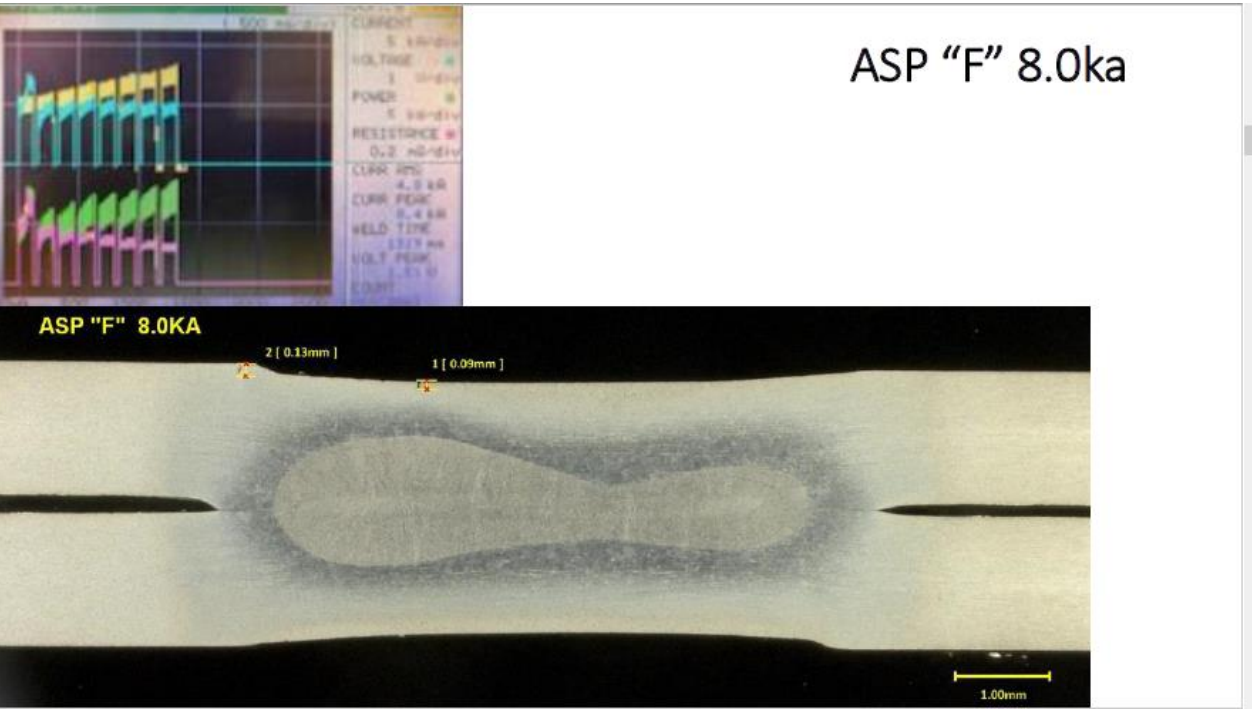

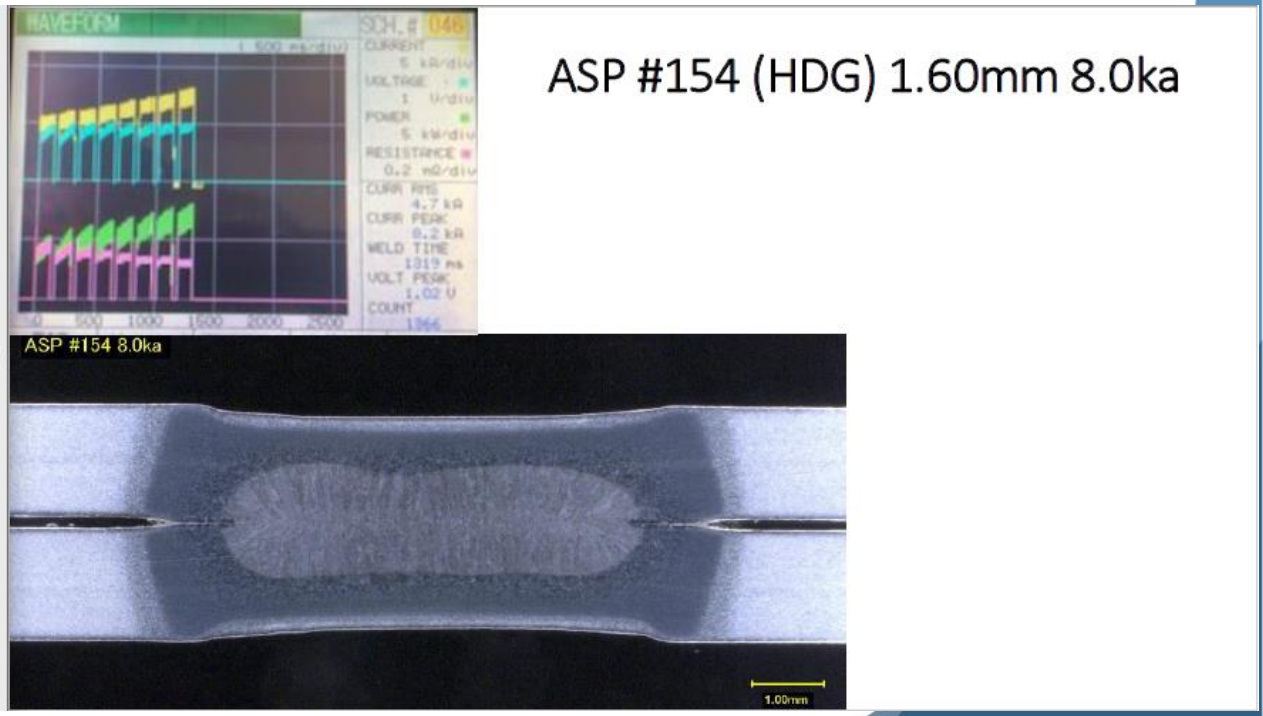

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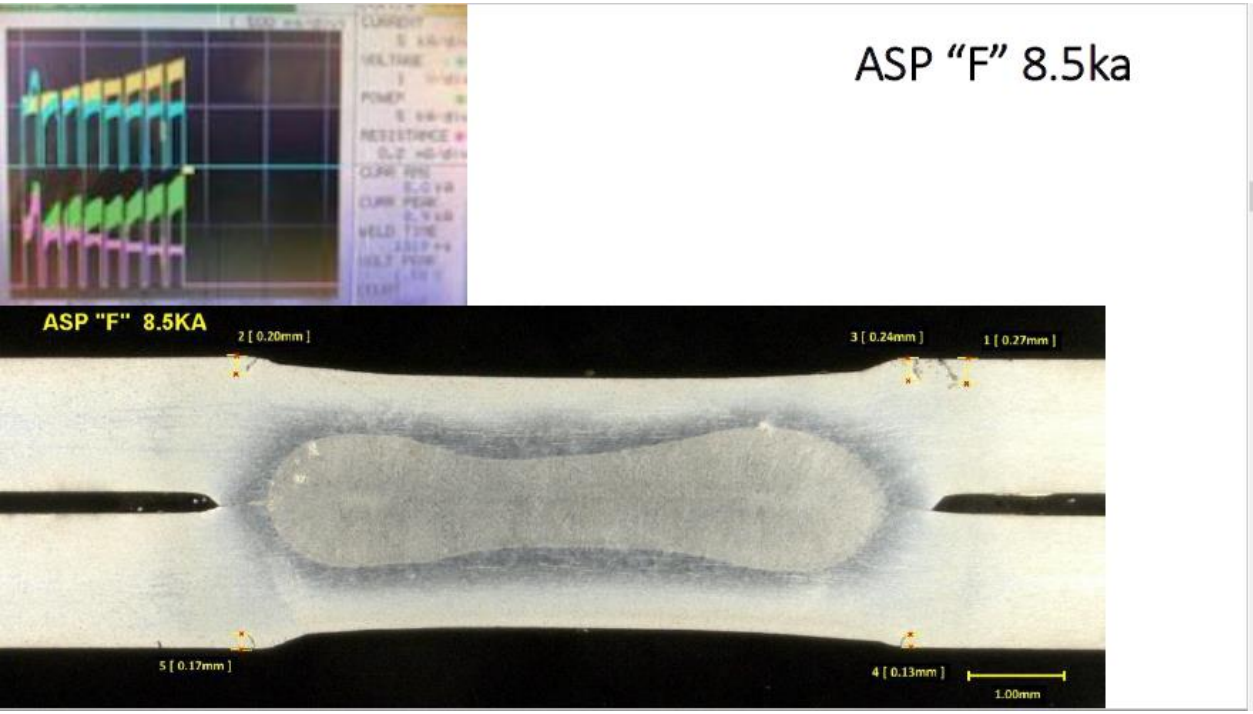
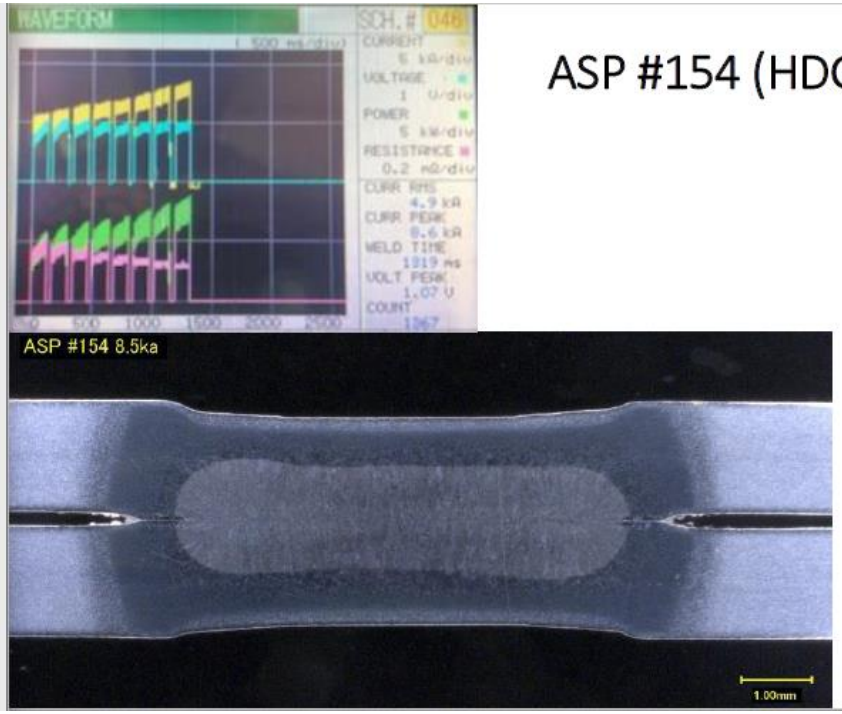


ASP “F” 8.5ka



ASP #154 (HDG) 1.60mm 8.5ka

Test Results for Bad and Good Steels

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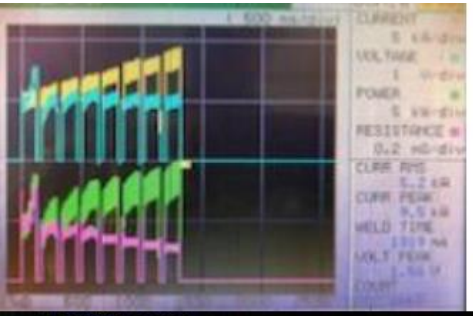
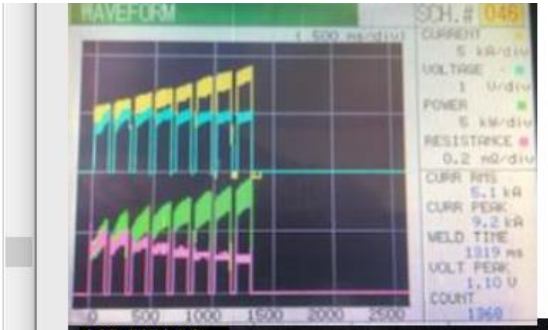
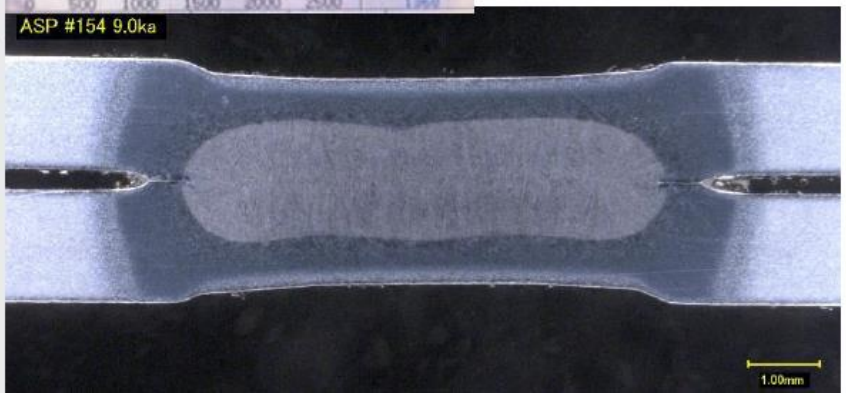
CR980T-600Y-RA-HE-GI
1.4mm



ASP “F” 9.0ka

Steel Lot #154
CR980T-600Y-RA-HE-GI
1.6mm





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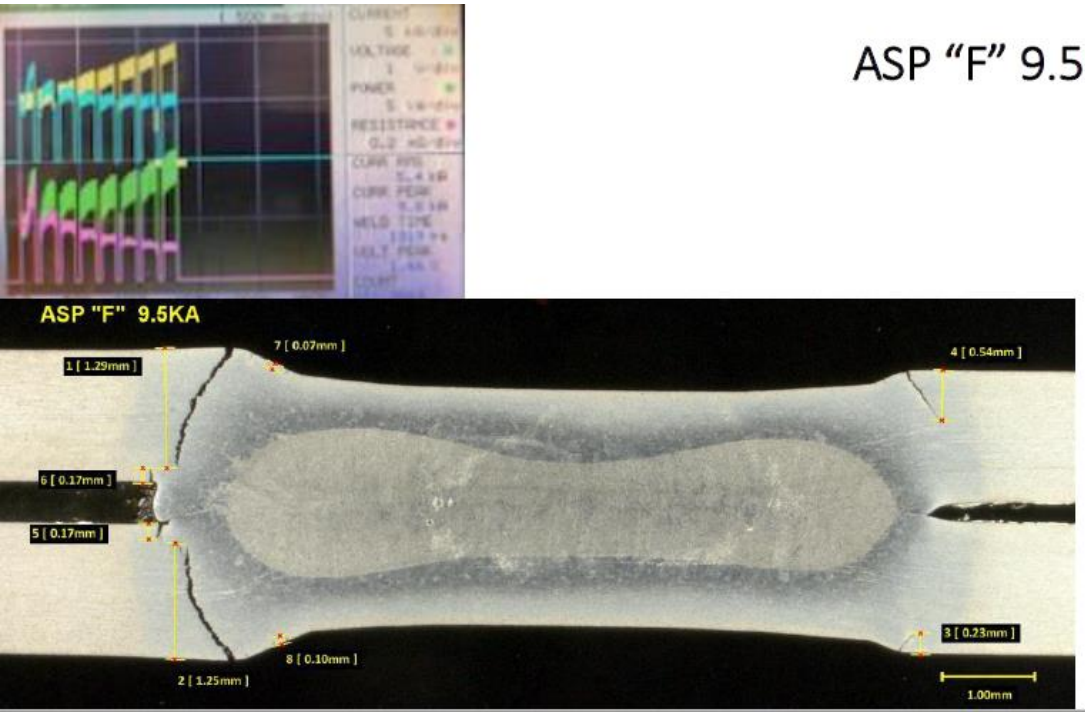

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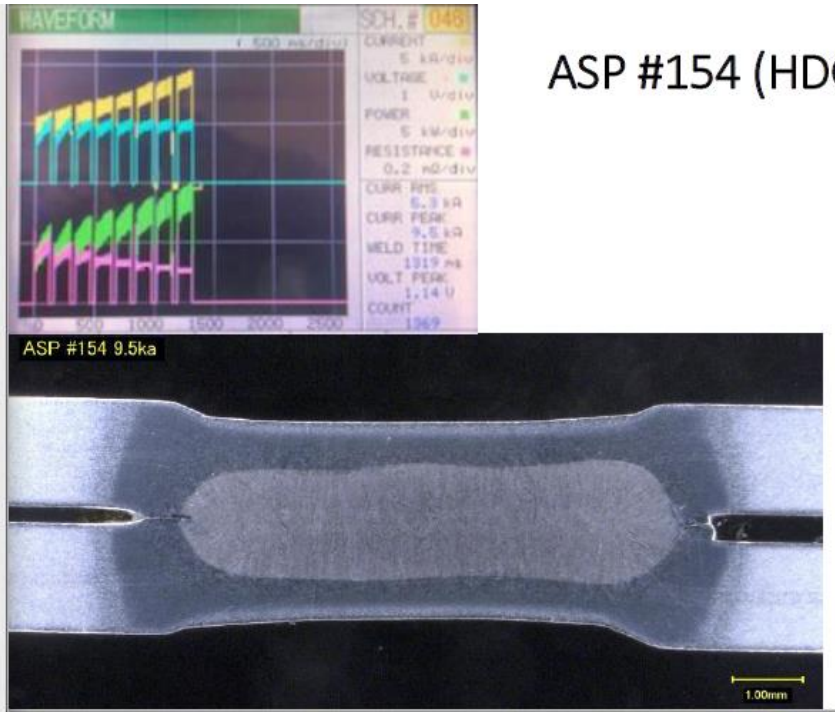

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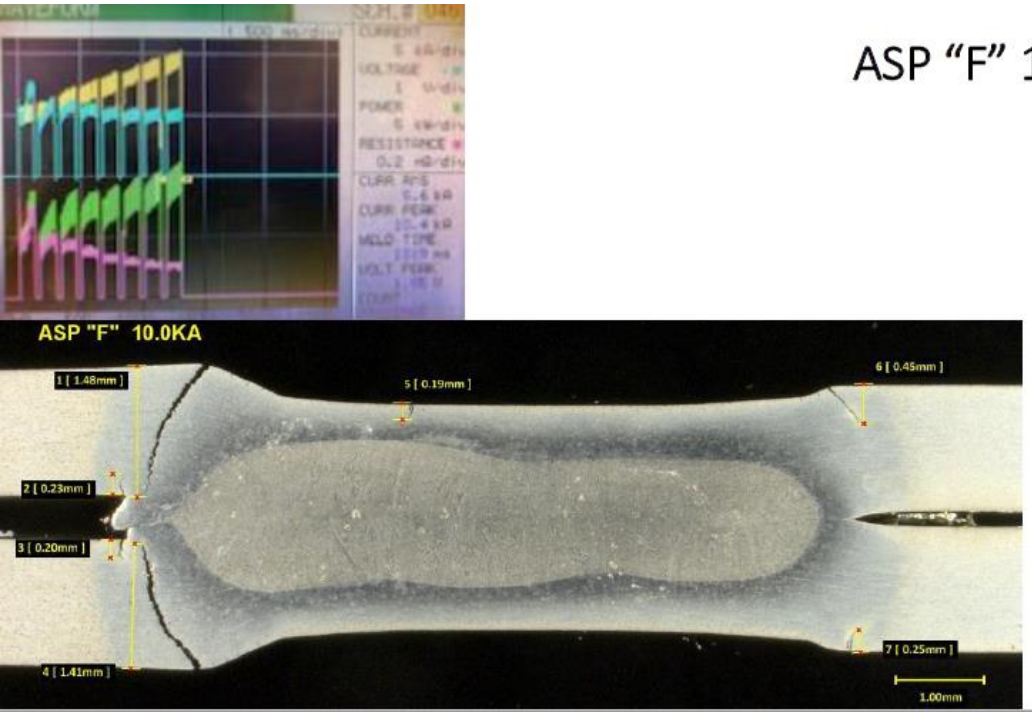

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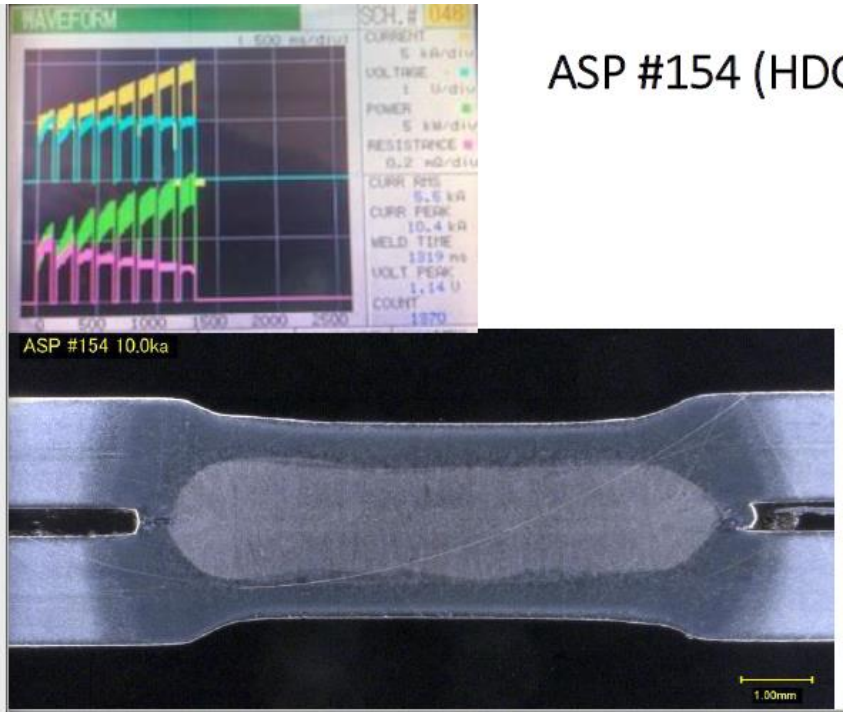

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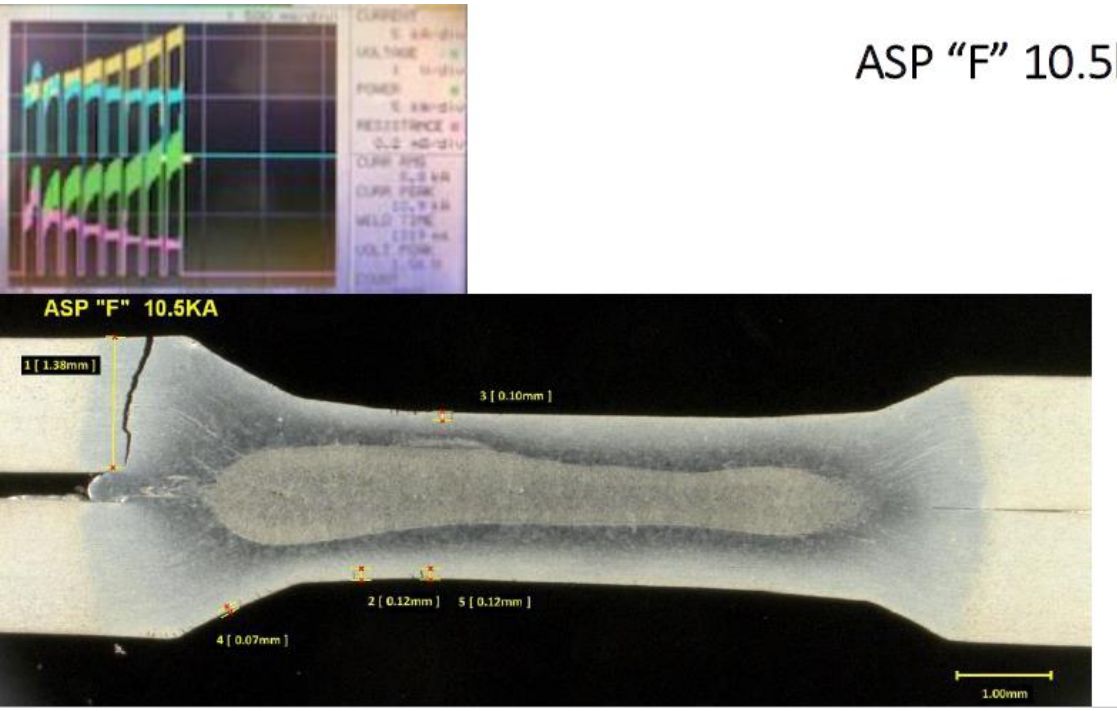

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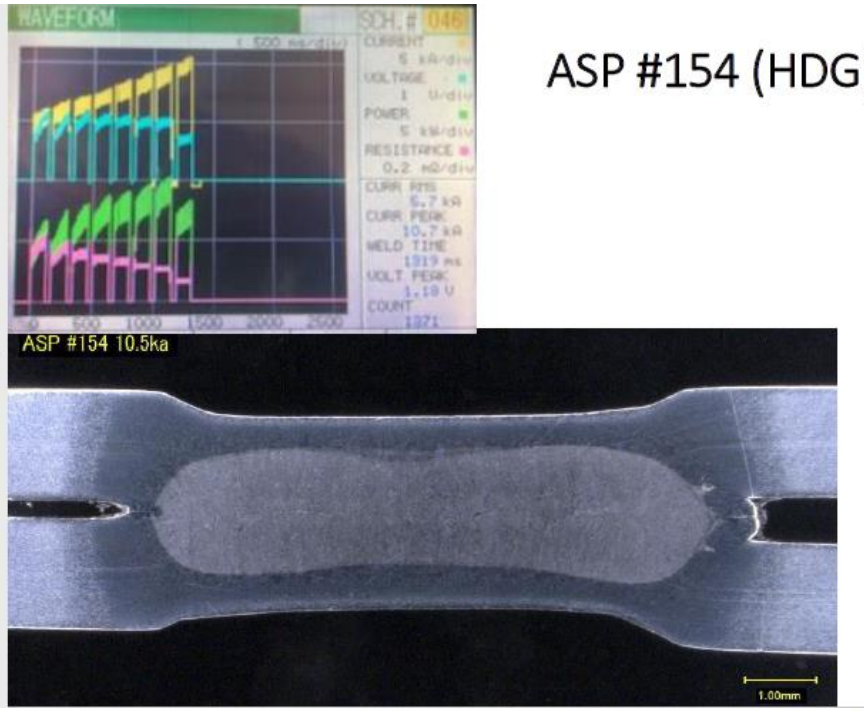

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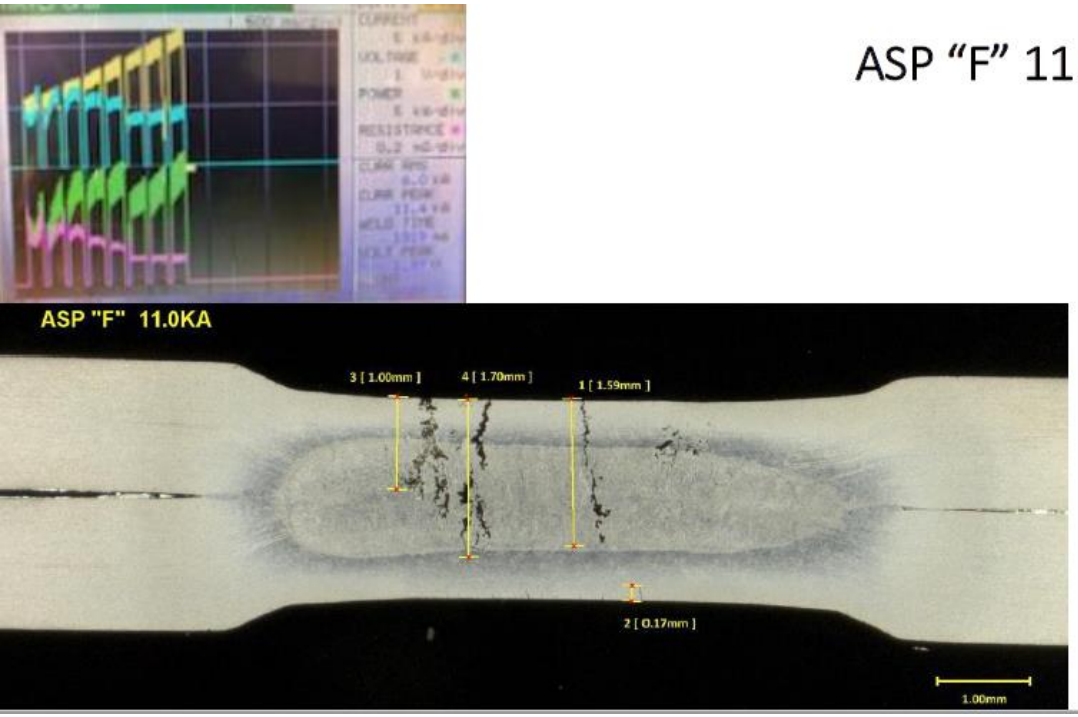

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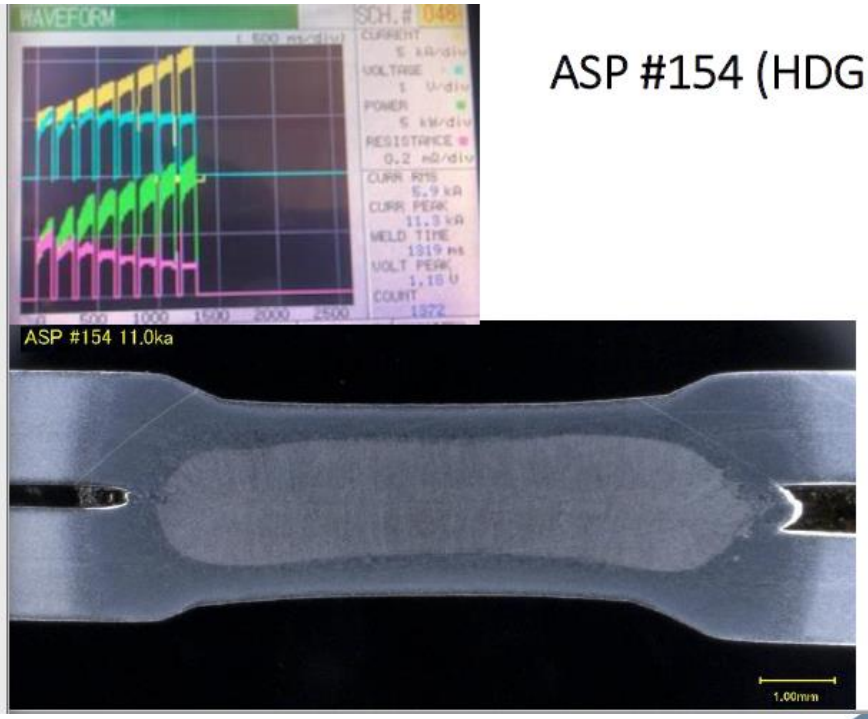

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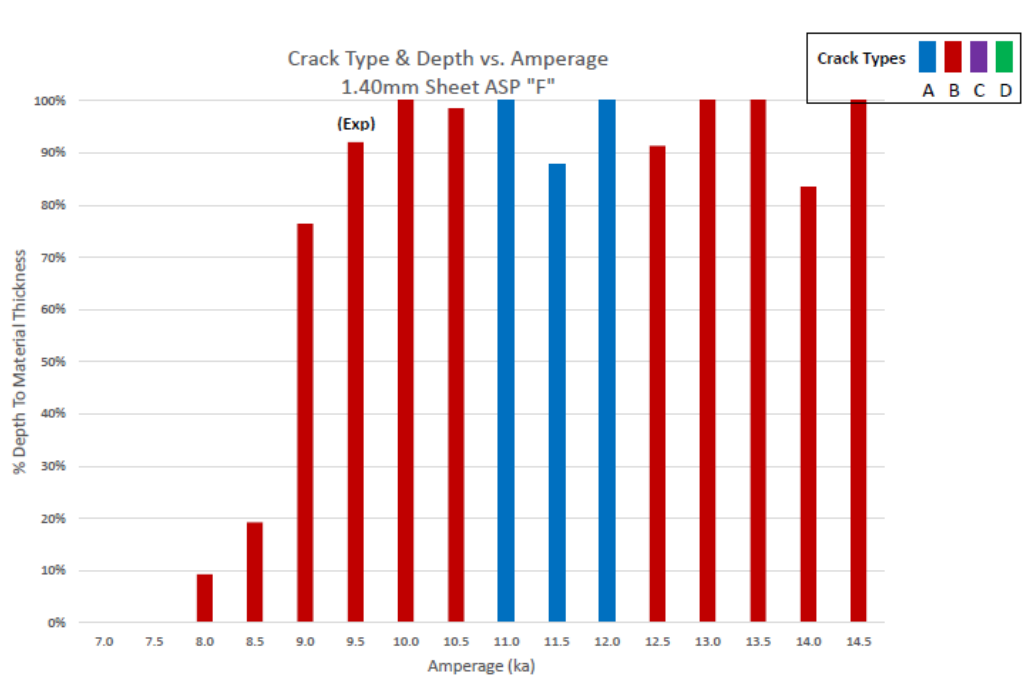

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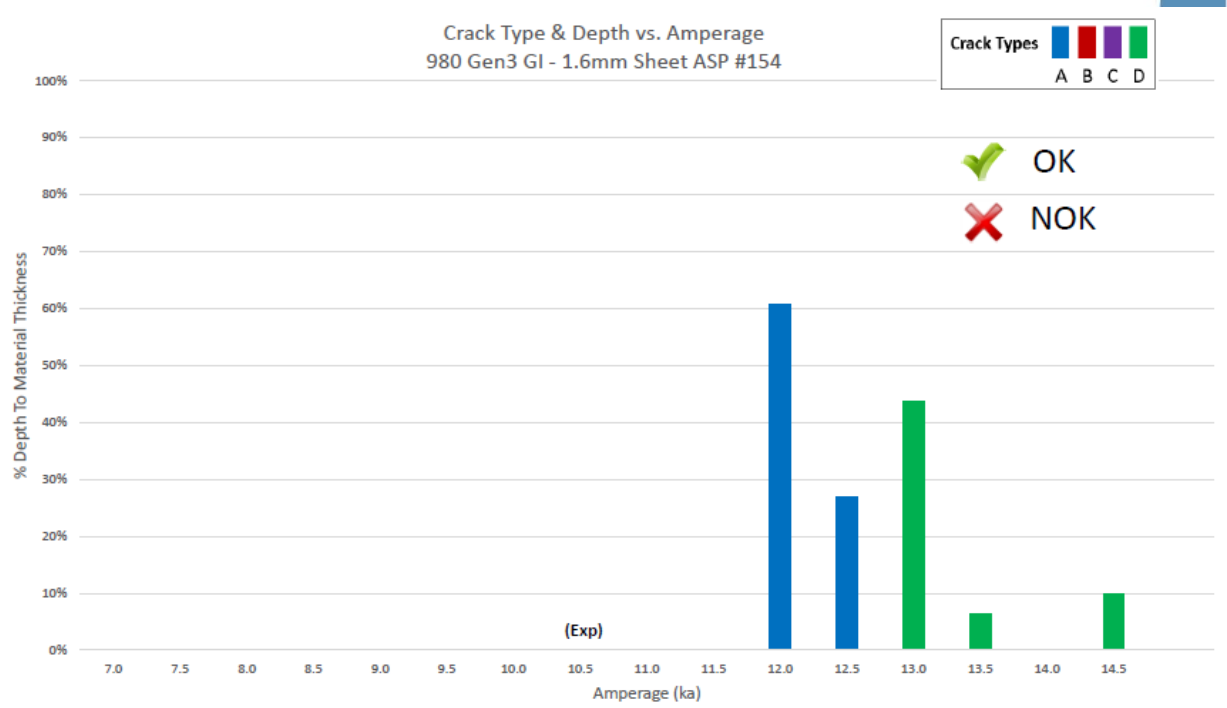
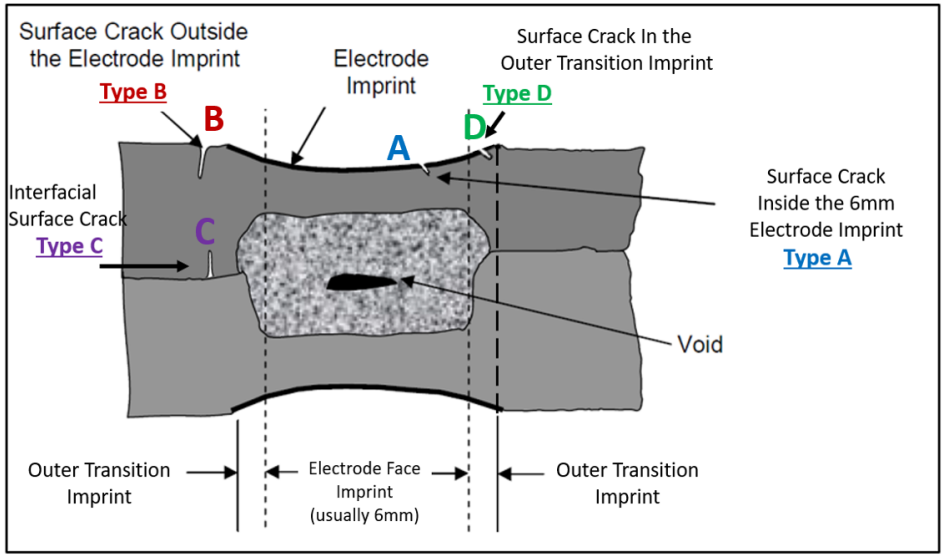


How to Interpret Results

Crack Location Map
used for test interpretation



General Acceptability of LME Cracks (By Location and Depth

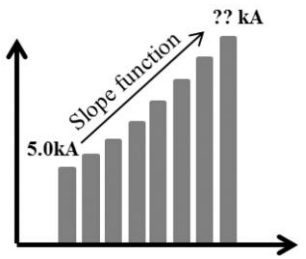
(THESE ACCEPTANCE CRITERIA APPLY TO THIS TEST PROCEDURE ONLY, AND DO NOT IMPLY A PRODUCT QUALITY STANDARD)

	Crack Location:			
	Type A	Type B	Type C	Type D
Relative Test Current	High Temp LME (>650C)	Low Temp LME (<650C)	Interfacial LME (? rare)	Threshold Temp LME (~650C)
Below Expulsion	OK if depth less than 10%	NOK	NOK	NOK
At (or above) Expulsion	OK	NOK	NOK	OK if depth less than 5%

Composite 3rd Gen LME Results for 2019

A/SP Rapid LME Test Results for 2019 Budget Year

Michael Karagoulis - Project Leader



Crack Types A B C D

LME Test Log Sheet

As of May 5, 2020

				Test Amperage (ka)															
Grade	Thick	Coat	Lot #	7.0	7.5	8.0	8.5	9.0	9.5	10.0	10.5	11.0	11.5	12.0	12.5	13.0	13.5	14.0	14.5	LME ka Rating
CR980T/600Y-RA-HE	1.0	EG	161					EXP	50%	5%	30%	30%	30%	20%	40%	50%	40%	50%		0.5 L
	1.6	EG	163				5%	10%	EXP 80%	40%	20%	10%	10%	40%	60%	100%	60%	60%	100%	-1.0 L
	1.0	GI	155								EXP 20%					5%	40%			0.0 M
	1.6	GI	154								EXP			60%	30%	40%	5%		10%	1.5 M
	1.4	GI	"F"			10%	20%	80%	EXP 90%	100%	100%	100%	90%	100%	90%	100%	100%	90%	100%	-1.5 L
	1.4	GI	116																	
	1.0	GA	185						EXP 65%	65%			100%	50%	100%	20%	100%	100%	70%	0.0 L
	1.6	GA	181								30%	EXP 60%	40%	20%	5%	60%	90%	80%	100%	-0.5 L
CR1180T/850Y-RA-SE	1.0	EG	178							EXP 70%	10%	10%	70%	40%	20%	60%	20%		40%	0.0 L
	1.6	EG	179									EXP 70%	30%	90%	80%	40%	40%	70%	10%	0.0 L
	1.0	GI	166		20%	60%	60%	60%	60%	60%	EXP 10%	80%	20%	40%	20%	40%	60%	50%	50%	-3.5 L
	1.6	GI	107	10%	20%	40%	50%	50%	60%	100%	80%	EXP 4%	100%	60%	70%					-4.0 L
	1.5	GI	"G"				10%		EXP 40%	70%	80%	30%	10%	60%	60%	20%	10%	50%	60%	-1.0 L
	1.0	GA	N.A.																	
	1.6	GA	N.A.																	

Project Conclusions

- A rapid LME screening test was developed for material characterization
- Results correlated well with Gleeble-based LME testing
- A variety of coated 3rd Gen lots were tested
- Results indicate a wide spectrum of LME sensitivity currently exists in the 3rd Gen supply base
- The test procedure has been made available to A/SP members to do their own material studies
- Galvanized (GI), electrogalvanized (EG) and galvanealed (GA) zinc coatings were evaluated, however limited testing did not suggest one coating was better than another.

Value Proposition

- The speed and low infrastructure of the rapid test procedure puts LME screening within reach of many:
  - A/SP member companies
  - Test labs
  - Universities
- Steelmakers are already applying the procedure to develop LME resistant steels, especially susceptibility to Low Temperature LME (type B cracking)
- Automakers are free to use the results for internal testing
- The procedure facilitates repeatable fabrication of cracked welds needed for mechanical testing, (for CAE studies, etc.)

Future Plans: Practical Application Challenges

- Continue the LME screening matrix
  - Other materials?
    - High Strength Low Alloy (HSLA), and Martensitic (MS) appear to be immune to Type B LME
    - 3rd Gen (RA), Dual Phase (DP), Multi-Phase (MP), and Complex Phase (CP) are not immune to Type B LME
    - Coating variables

- Use the LME scores to study whether LME susceptibility matters to vehicle performance
  - B.O.B & W.O.W. tests (best of the best vs. worst of the worst)
  - Various RSW joint configurations
  - Does LME Exist with other common welding processes
    - Gas Metal Arc Welding?
    - Drawn arc?
    - Laser?

Bead-on-plate GMAW weld on a material with high LME susceptibility

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Thank You / For More Information

Contacts:

Kevin Teng – Zhenke.teng@gm.com
A/SP LME Project Leader
(586) 449-4889

Hassan Ghassemi-Armaki - Hassan.ghassemi@arcelormittal.com
A/SP Joining Team Lead
(219) 399-5860

Eric McCarty - emccarty@steel.org
A/SP Project Manager
(248) 945-4778

Auto/Steel Partnership