Advancing LME Understanding: Standardized Characterization and Direct Observation in Resistance Spot Welding

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CONTENTS

Introduction
- RSW process
- LME
- Existing LME testing method
- Half-sectioned welding
- Research Motivation

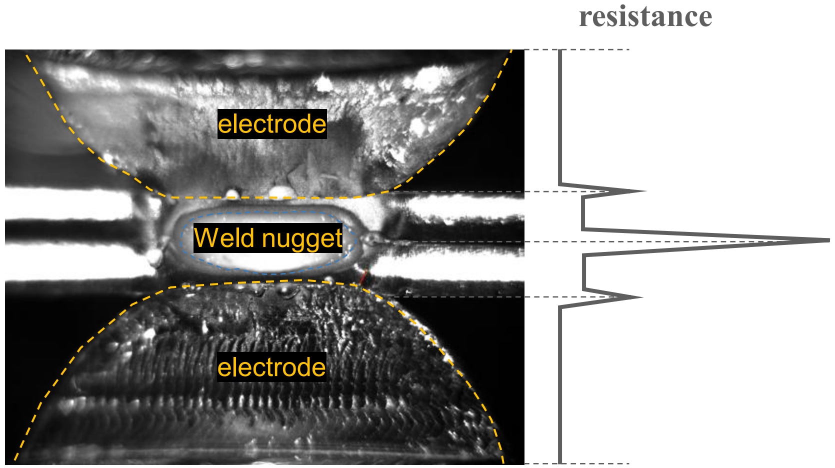
Task 1
- LME testing & Characterization
- Determining Best LME Characterization Method

Task 2
- Kinetics of LME cracks Propagation
- Effect of temperature difference at crack tip on crack growth rate

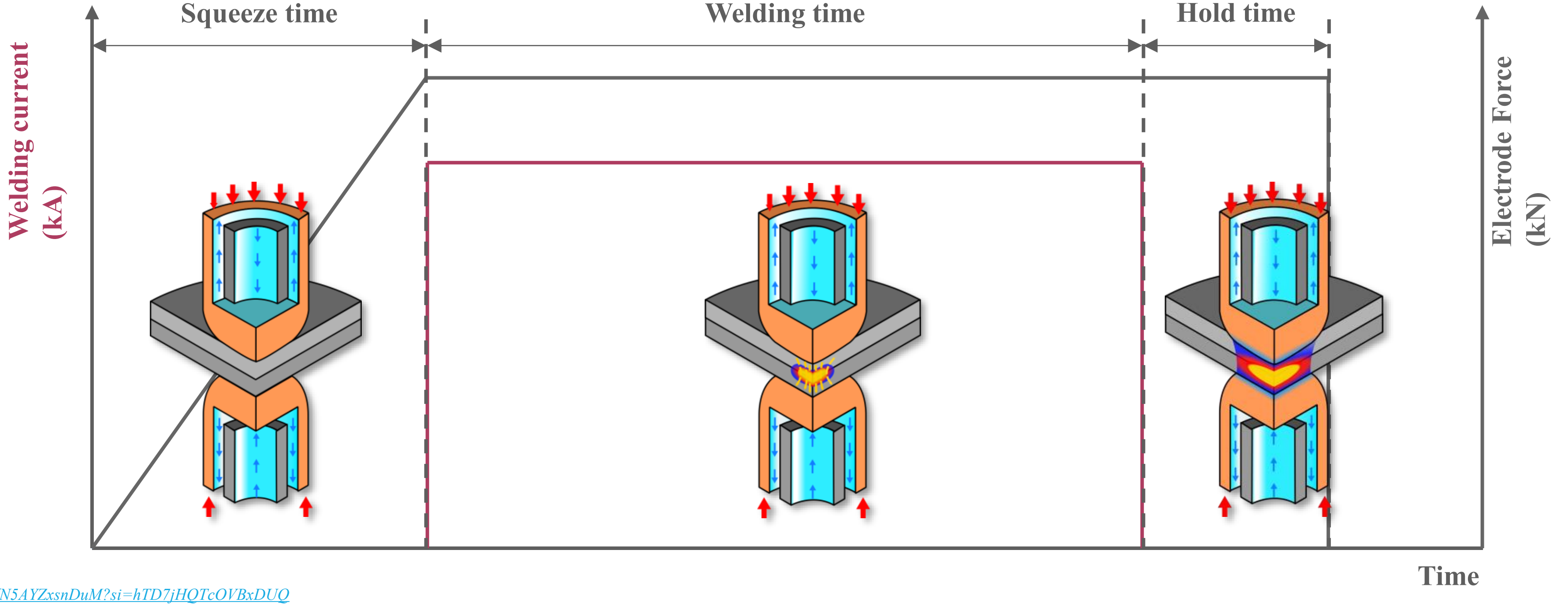
Conclusions
- Main Conclusions

Resistance Spot Welding Process

GDIS

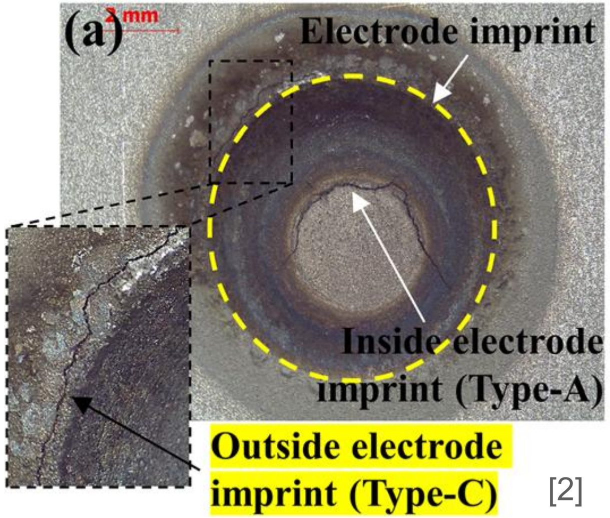


$$Q\text{ (heat)} = \int_0^t I^2(t)R(t)dt$$

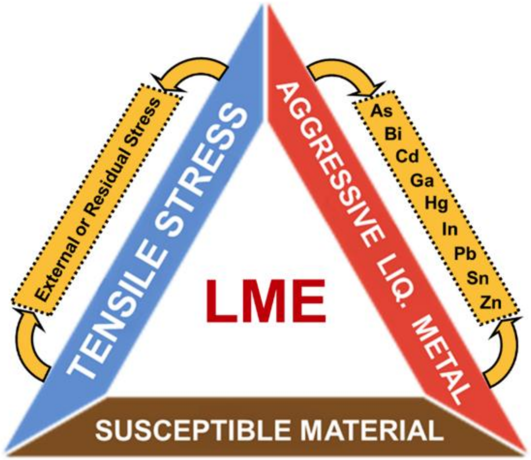


[1] *Resistance spot welding link:* https://youtu.be/N5AYZxsnDuM?si=hTD7jHQTcOVBxDUQ

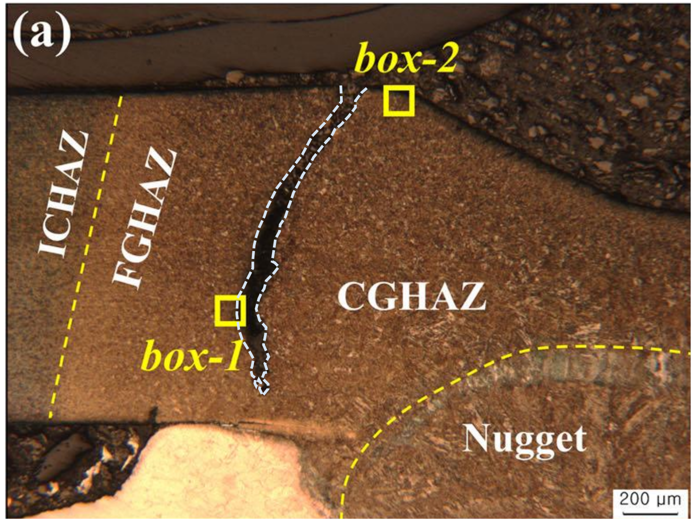
Liquid Metal Embrittlement (LME)



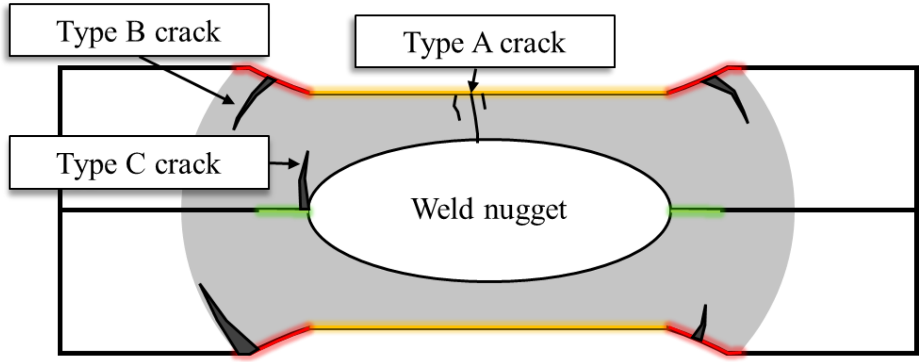
[2]



[3]



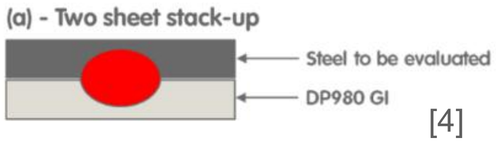
[2]



[2] *Murugan, S. P., et al. Liquid Zinc penetration induced intergranular brittle cracking in resistance spot welding of galvannealed advanced high strength steel. Welding in the world. (2020) 64:1957-1969.*
[3] *Razmpoosh, M. et al. Pathway to understand liquid metal embrittlement (LME) in Fe-Zn couple: From fundamentals toward application. Progress in Materials Science (2021) 121.*

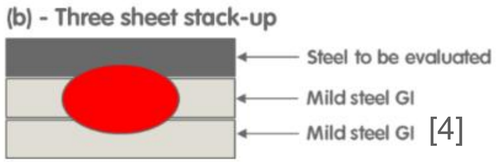
LME Testing and Characterization Methods

Testing



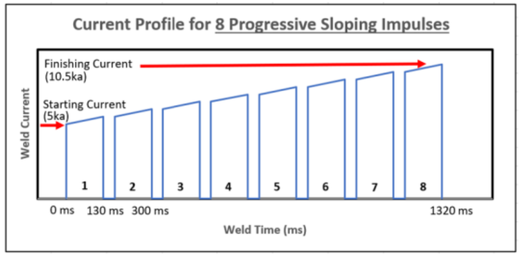
[4]

2-High Spot Welds



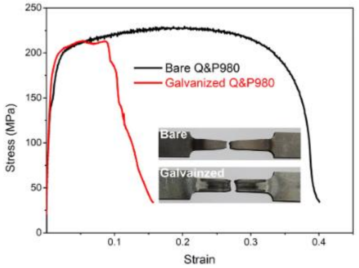
[4]

3-High Spot Welds



[5]

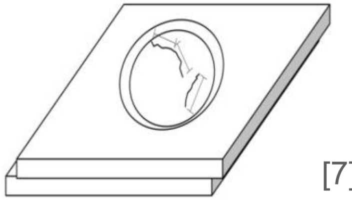
A/SP Rapid LME Test



[6]

Hot Tension Testing (Gleeble)

Characterization



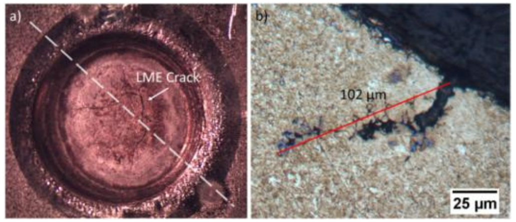
[7]

Surface Crack Measurement

	4 Crack Types by Relative Temperature:			
	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	> 10% NOK	> 5% NOK	> 5% NOK	> 5% NOK
At (or above) Expulsion	OK	> 5% NOK	> 5% NOK	> 10% NOK

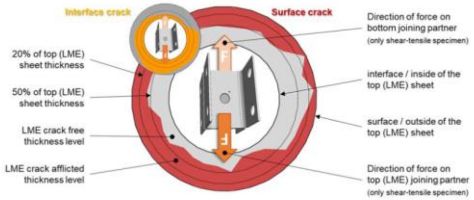
[5]

Cross-section Crack Classification



[8]

Cross-section Crack Measurement



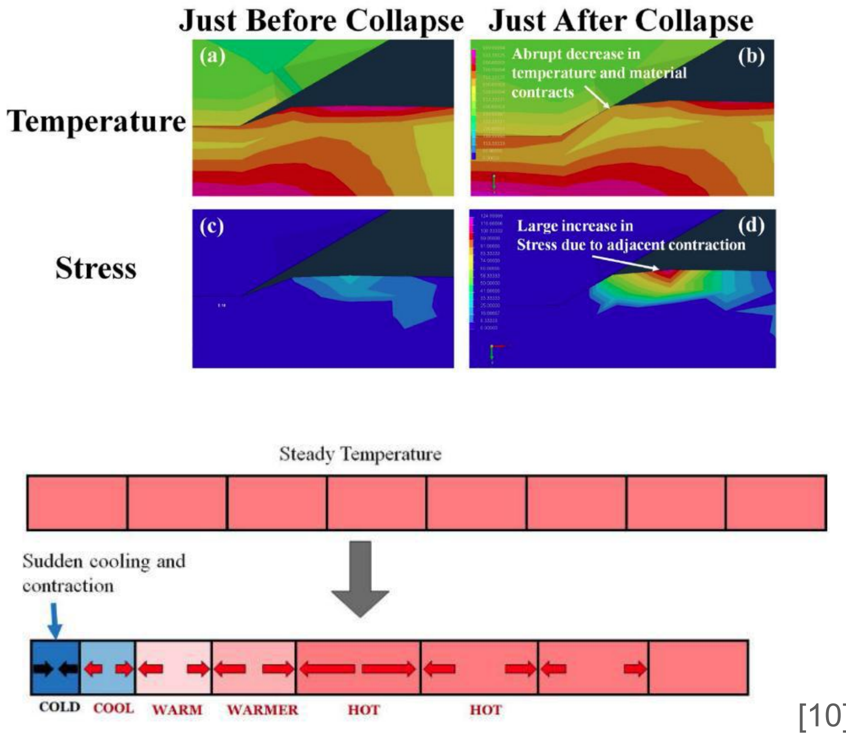
[9]

Computed tomography (CT) Scanning

There is no standardization in testing or LME severity metrics

[4] D. Benlatreche et al., The 72nd annual assembly of the International Institute of Welding (IIW) (2019).
[5] M. Karagoulis, General Motors, (2019).
[6] Z. Ling et al., Materials & Design, (2020).
[7] E. Tolf et al., Science and Technology of Welding and Joining, (2013).
[8] E. Wintjes et al., Welding in the World, (2019).
[9] G. Meschut et al., World Auto Steel, (2020).

Thermal Stress Development at the Weld Shoulder



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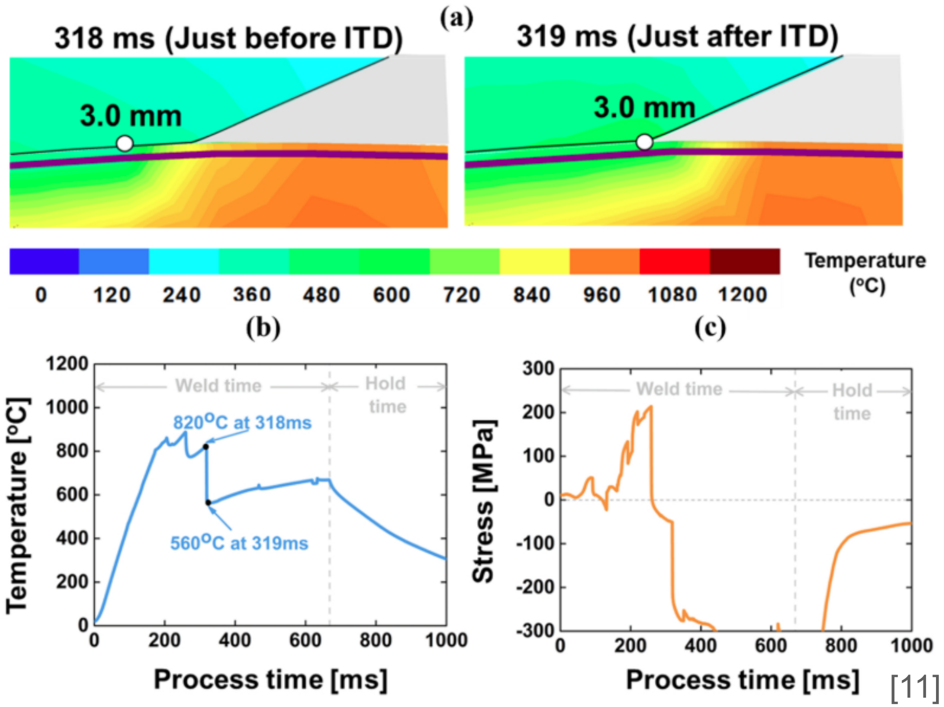


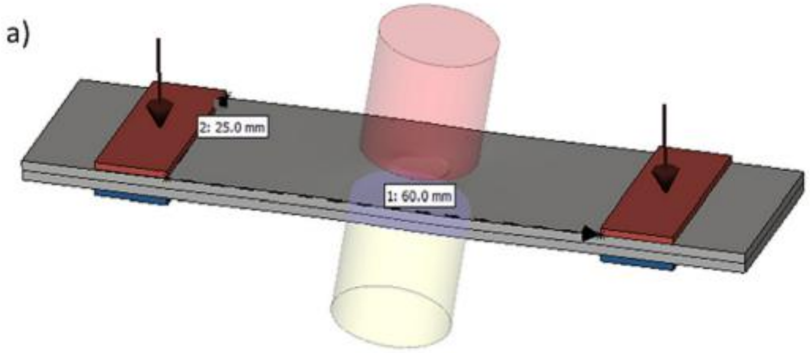
[11]

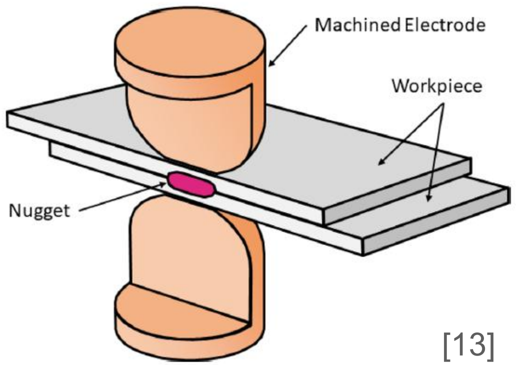
Electrode-to-sheet contact induces an instantaneous temperature drop (ITD), causing thermal stress

Thermal stress plays a dominant role in LME crack during the RSW process

[10] DiGiovanni G. et al. Role of spot weld electrode geometry on liquid metal embrittlement crack development. Journal of Manufacturing Processes (2020) 49:1-9
[11] *Lalachan A. et al. Liquid metal embrittlement in Zn-coated steel resistance spot welding: Critical electrode-contact and nugget growth for stress development and cracking. (2023) 318.*

Half-Sectioned Resistance Spot Welding (H-RSW)





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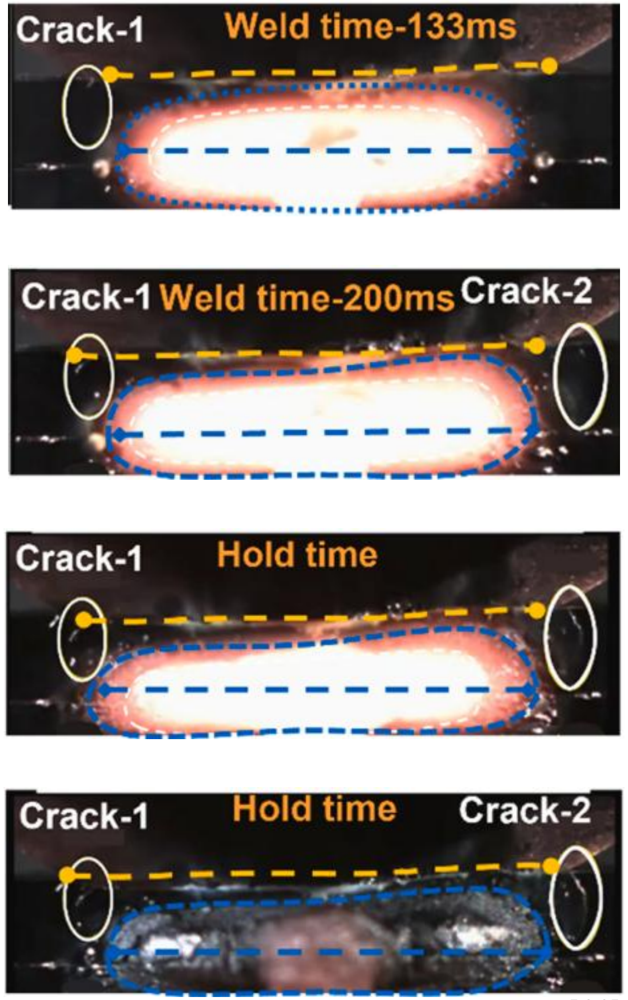
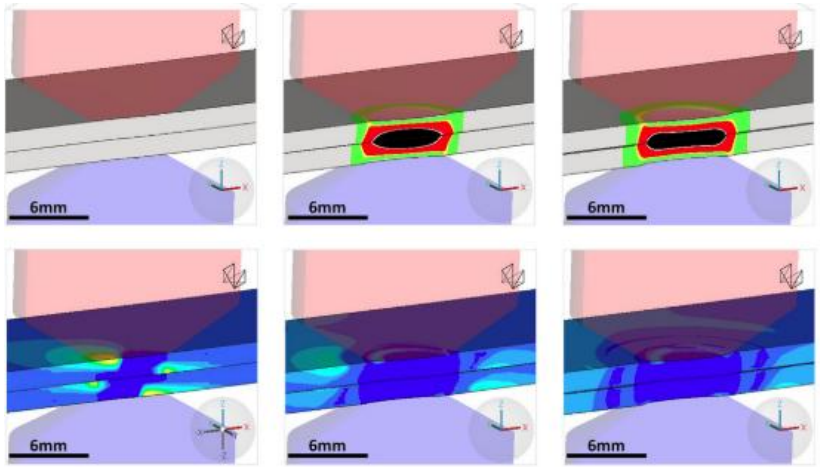




[11]

No Quantitative analysis on LME crack during the actual spot-welding environment

[11] Lalachan A. et al. *Liquid metal embrittlement in Zn-coated steel resistance spot welding: Critical electrode-contact and nugget growth for stress development and cracking. (2023) 318.*
[12] Okigami, F. et al. *Numerical modeling of liquid metal embrittlement initiation during resistance spot welding of third generation advanced high strength steel-Effect of welding schedule and electrode alignment. Journal of Manufacturing Processes. (2024) 110:173-191.*
[13] Brizes. E. et al. Evaluation of heat transfer within numerical models of resistance spot welding using high-speed thermography. Journal of Materials Processing Technology. (2021) 297

Motivation

Goals of each task

- **Task 1:**

? Since there is **no standardization** in LME testing or severity metrics, so current data cannot be compared

A **standard LME testing** and **measurement methodology** must be developed to compare LME severity results to both each other and to expected results during manufacturing

- **Task 2:**

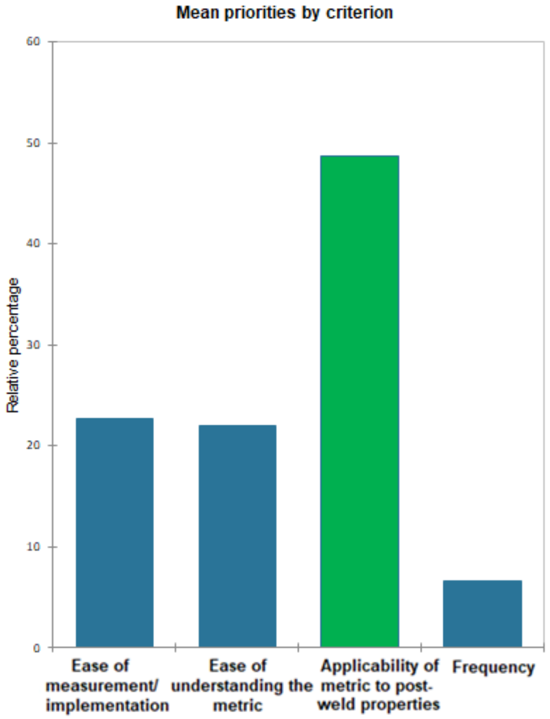
? What are the **growth kinetics** (e.g., crack growth rate) and **key factors** controlling LME crack propagations?

Quantitative analysis on LME crack **propagation** using various electrode geometries to determine key factors controlling LME crack propagation.

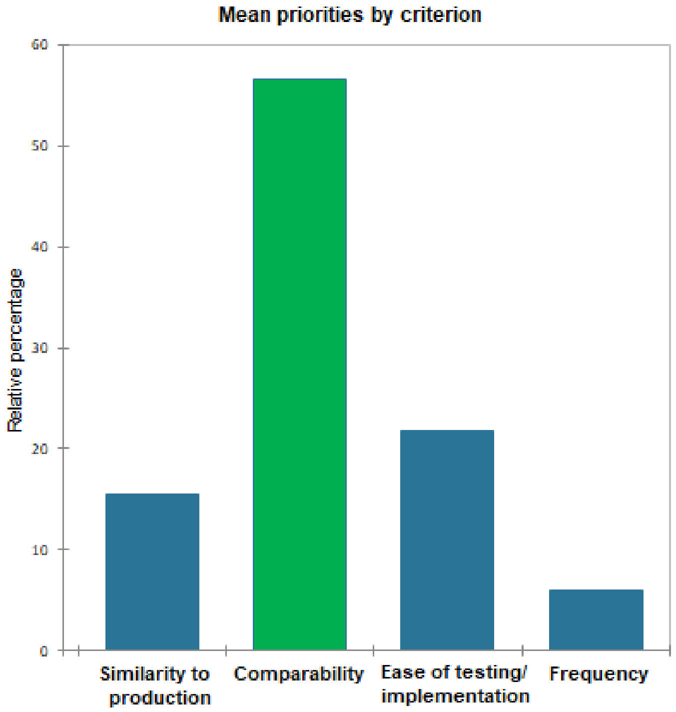
Testing and Characterization Comparison

Testing and characterization procedures were evaluated using both the **Delphic Hierarchy Process** and the **Analytic Hierarchy Process**. These methods were used to compare various methodological options and identify which test should be considered.

Characterization



Testing



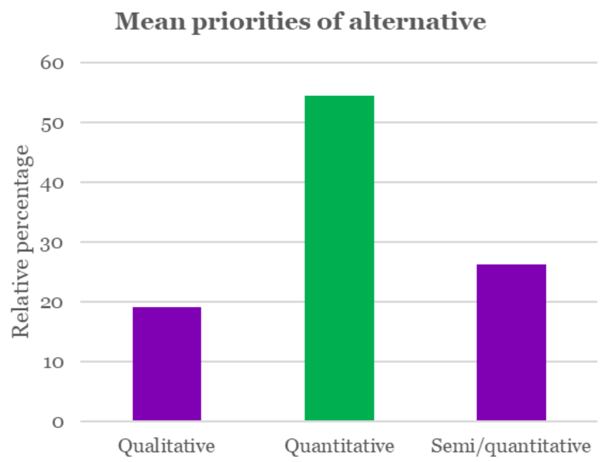
LME Characterization Option Priorities

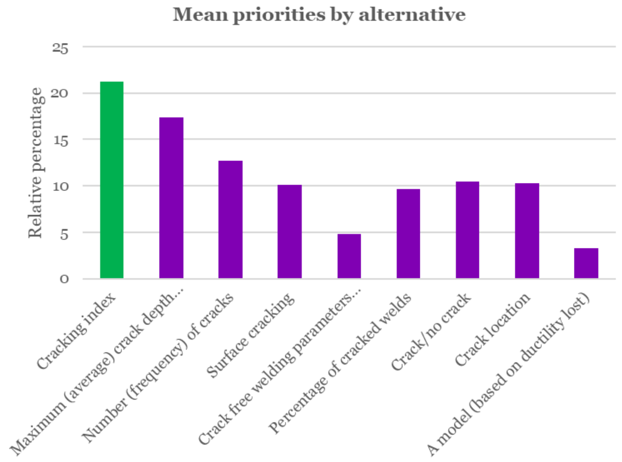
Type of metric
Qualitative
Quantitative
Semi/quantitative

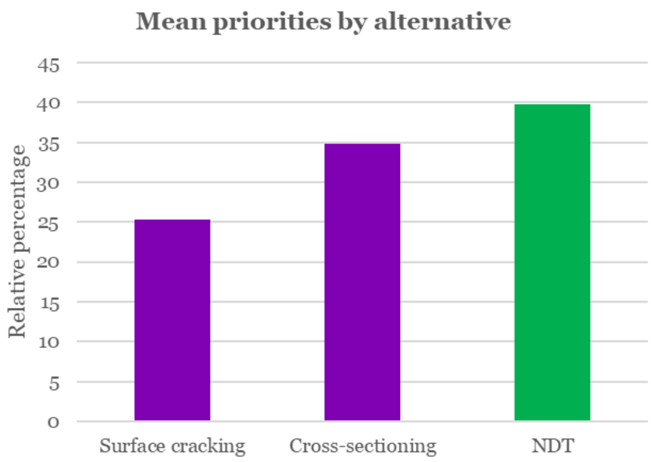
Definition of metric
Cracking index
Maximum (average) crack depth (length)
Number (frequency) of cracks
Surface cracking
Crack free welding parameters (current)
Percentage of cracked welds
Crack/no crack
Crack location
A model (based on ductility lost)

Characterization method
Surface cracking
Cross-sectioning
NDT

Increasing the priority of alternatives







LME Testing Option Priorities

Stack-up
Similar two-sheet
Dissimilar two-sheet
Similar three-sheet
Dissimilar three-sheet
Complex stack-up

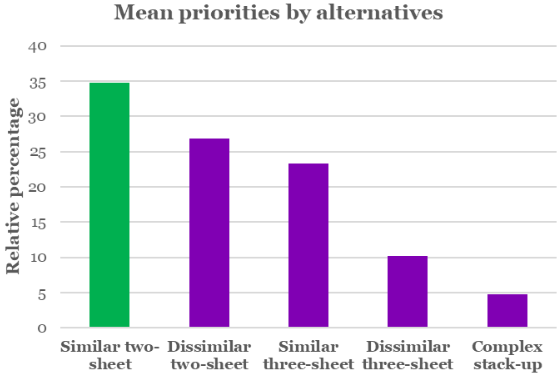
Welding current	
Imax	Single-pulse
Imax-a%	Two-pulse (Multiple-pulse)
Imax+a%	Sloping impulses
Definite value	

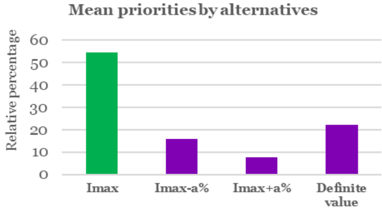
Electrode
Based on a standard
Definite type
Different types

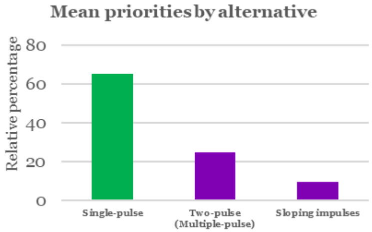
Nugget size
Fixed
Variable (not applicable)

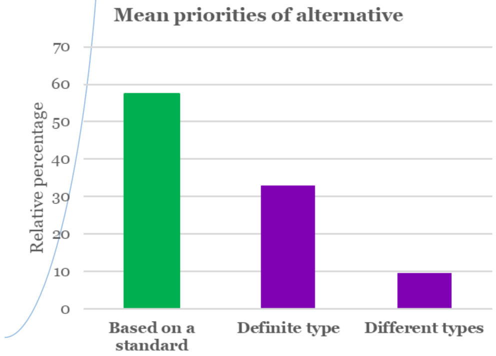
No. of tests
Not defined
1 to 10
More than 10

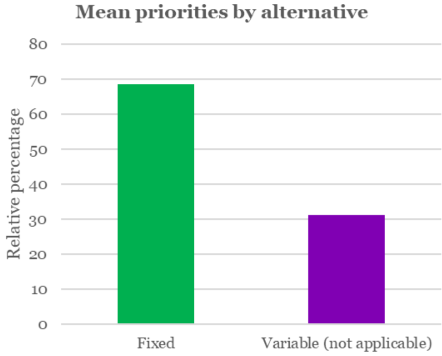
Increasing the priority of alternatives

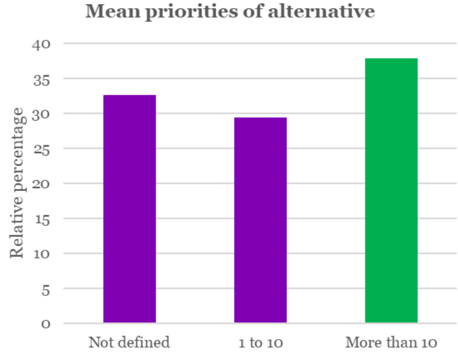












Results of Testing and Measurement Comparisons

GDIS

	Type of metric	Definition of metric	Characterization method
LME characterization alternatives	Quantitative	Cracking index	Cross-sectioning

	stack-up	welding current		Electrode	Nugget size	No. of tests
LME testing alternatives	Similar two-sheet	Imax	Single-pulse	Based on a standard	Fixed	More than 10

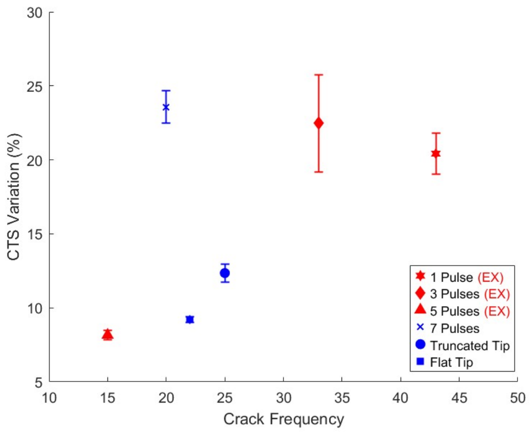
Determining Best LME Characterization Method

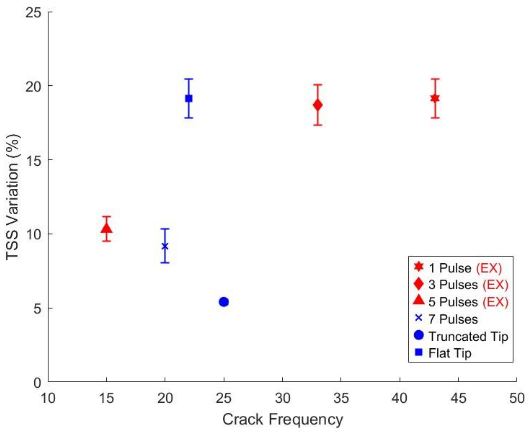
GDIS

Correlation of Cracking and Welding Strength – Maximum Crack Length, Average Crack Length, and Crack Frequency

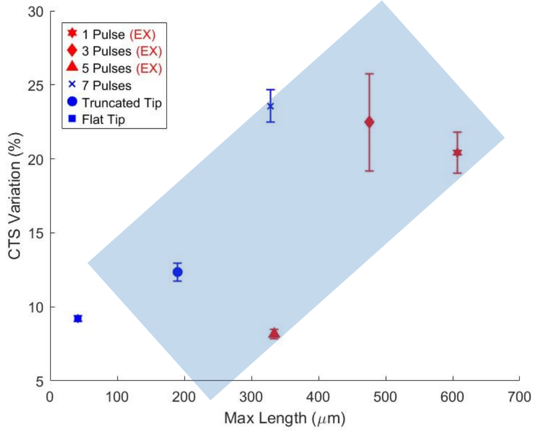
CTS | TSS | CTS | TSS

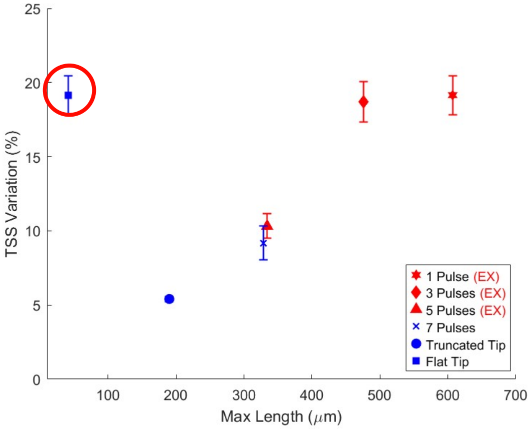
Crack Frequency



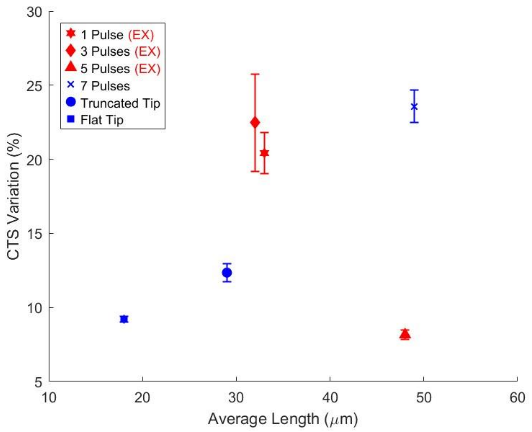


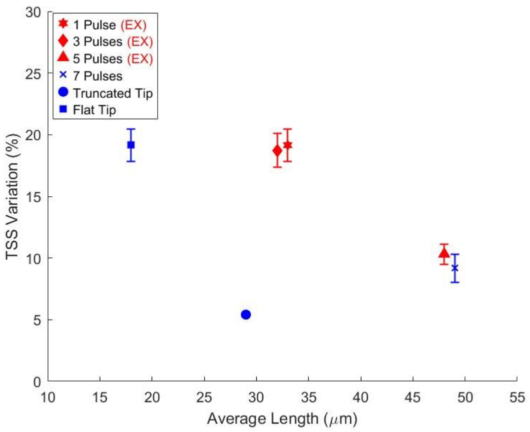
Max Length





Average Length



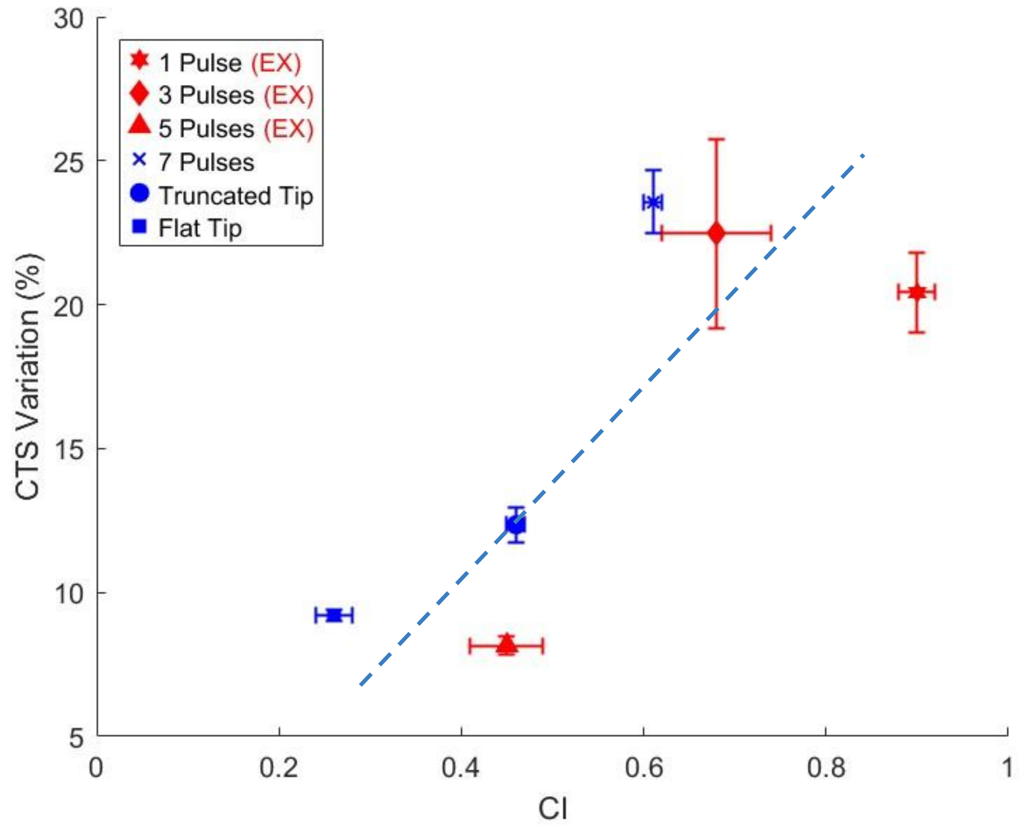


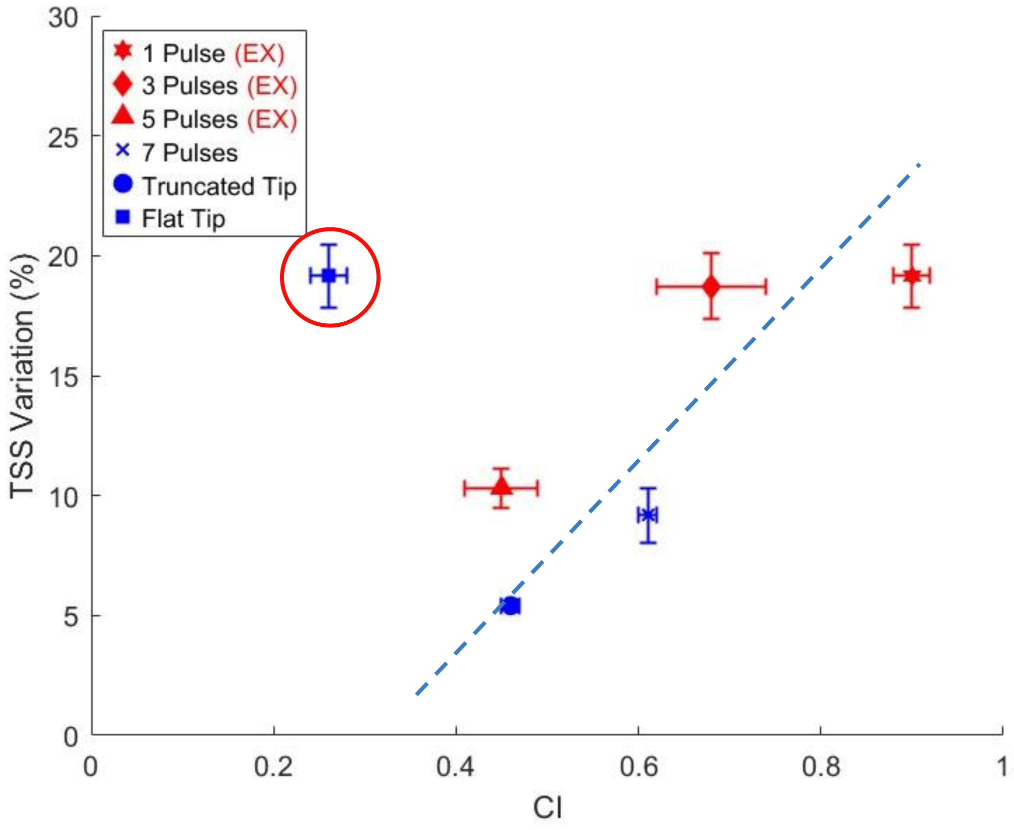
- Crack frequency is a poor indicator of CTS and TSS.
- Average crack length is a poor indicator of CTS and TSS; TSS increases with average crack length.
- Max crack length is a good indicator of TSS, but there is a wide spread of the CTS data.

*CTS: Cross tensile strength
*TSS: Tensile shear strength

Determining Best LME Characterization Method

Correlation of Cracking and Welding Strength – Cracking Index





Cracking Index is a good Indicator or CTS and TSS

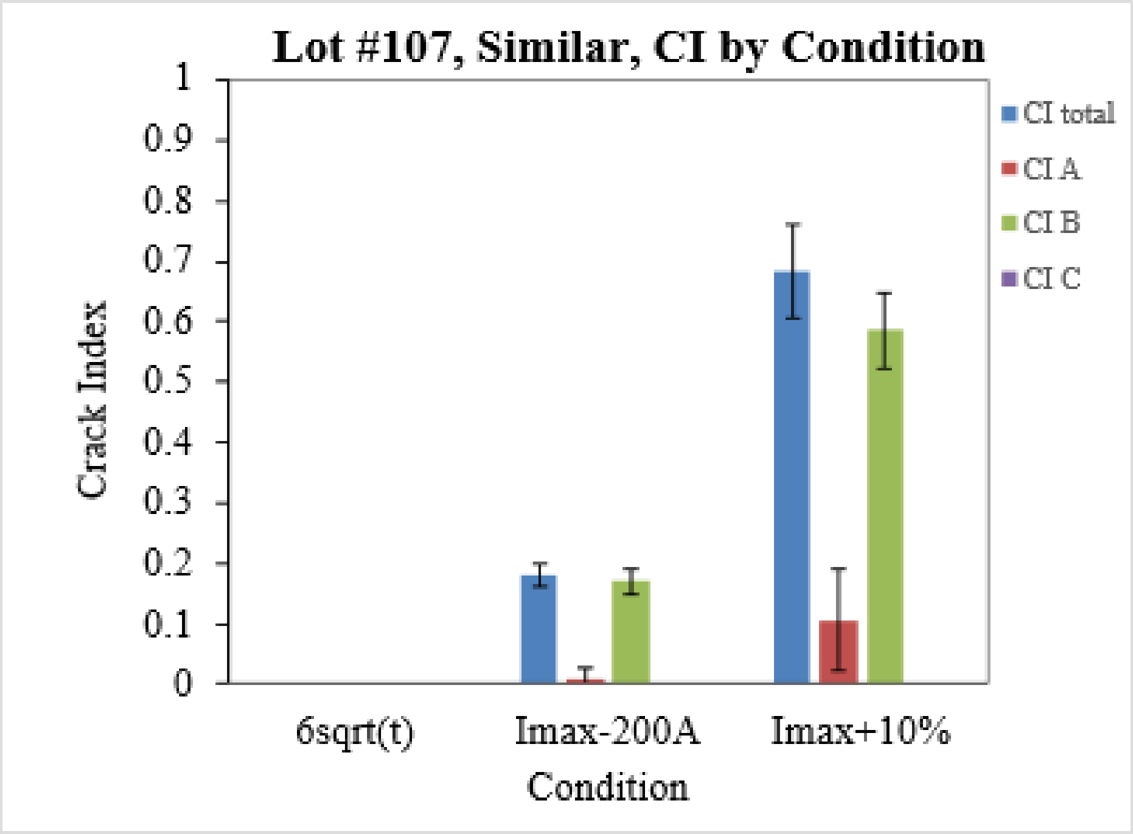
*CTS: Cross tensile strength
*TSS: Tensile shear strength

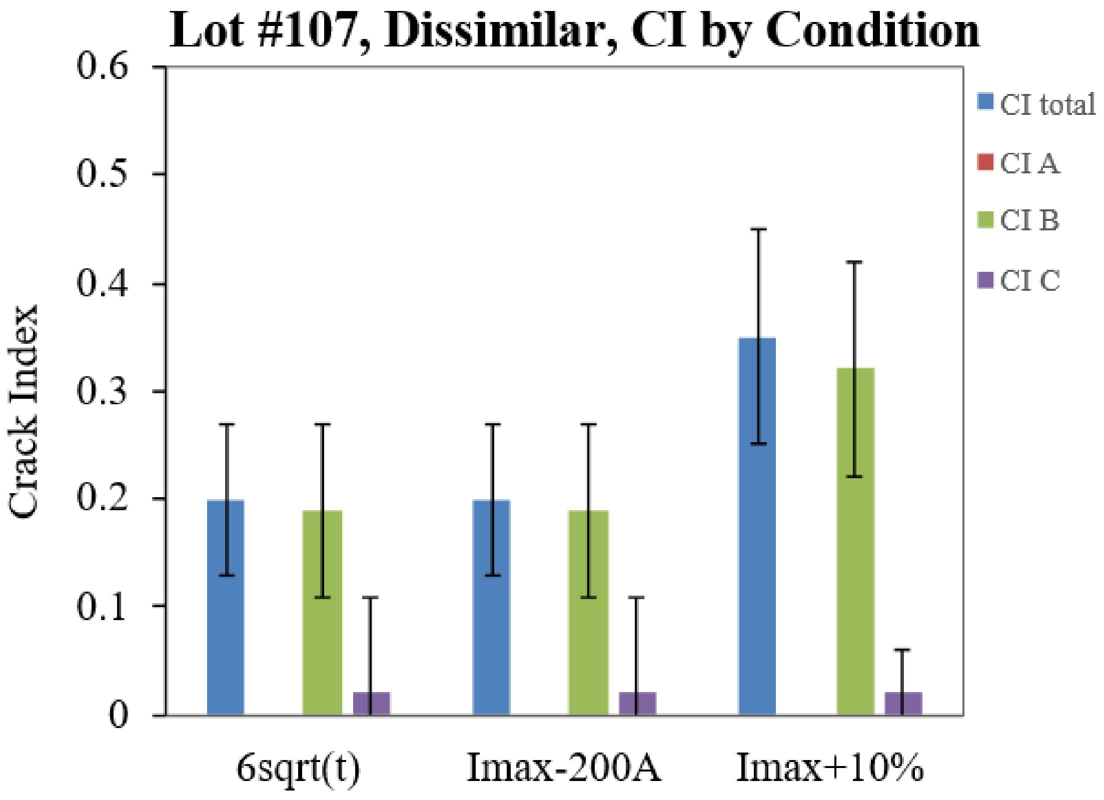
Crack Index Method Validation

Similar/dissimilar stack-up comparison/effect of current level on LME susceptibly

AHSS
AHSS
← **Similar stack-up**

Mild
AHSS
← **Dissimilar stack-up**





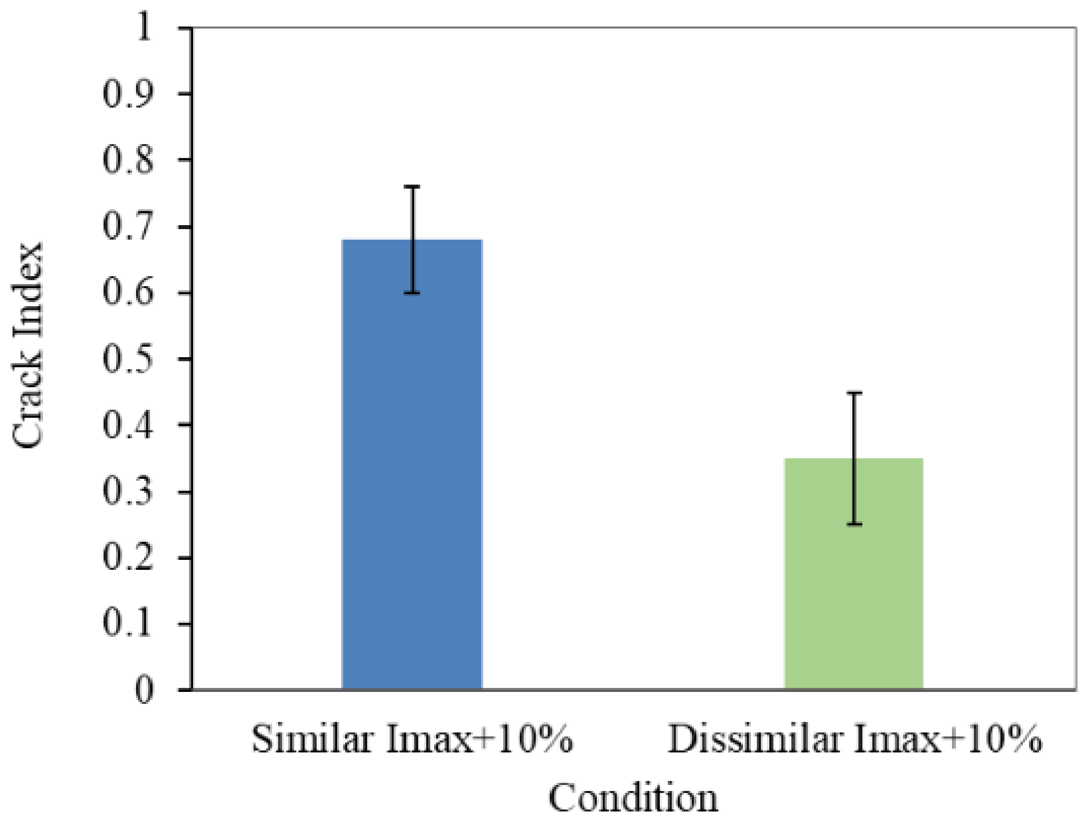
I_{min}: Current meet minimum requirement of nugget size ($6\sqrt{t}$)
I_{max}: highest current at which no expulsion occurs in ten consecutive welding trials

Crack Index Method Validation

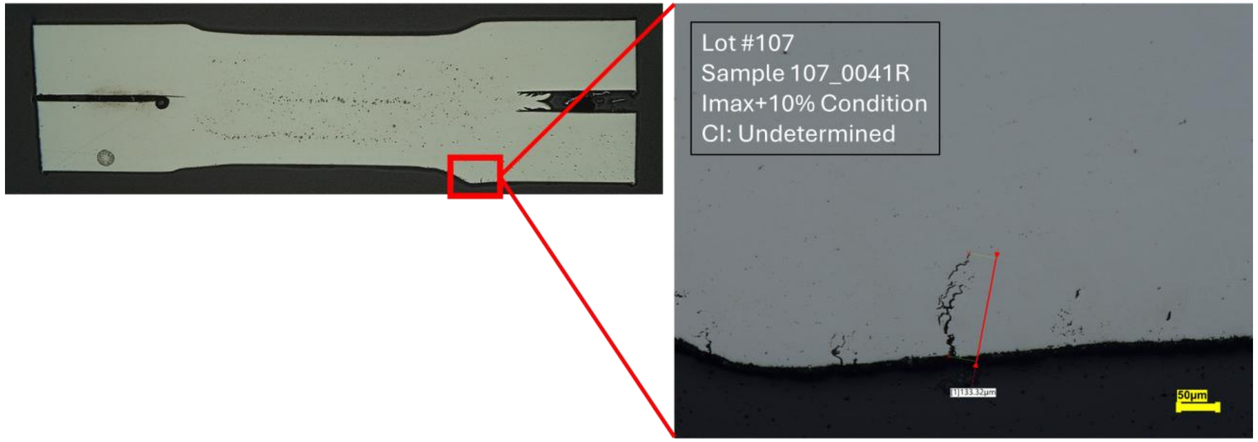
Similar/dissimilar stack-up comparison/effect of current level on LME susceptibly

AHSS
AHSS
← **Similar stack-up**

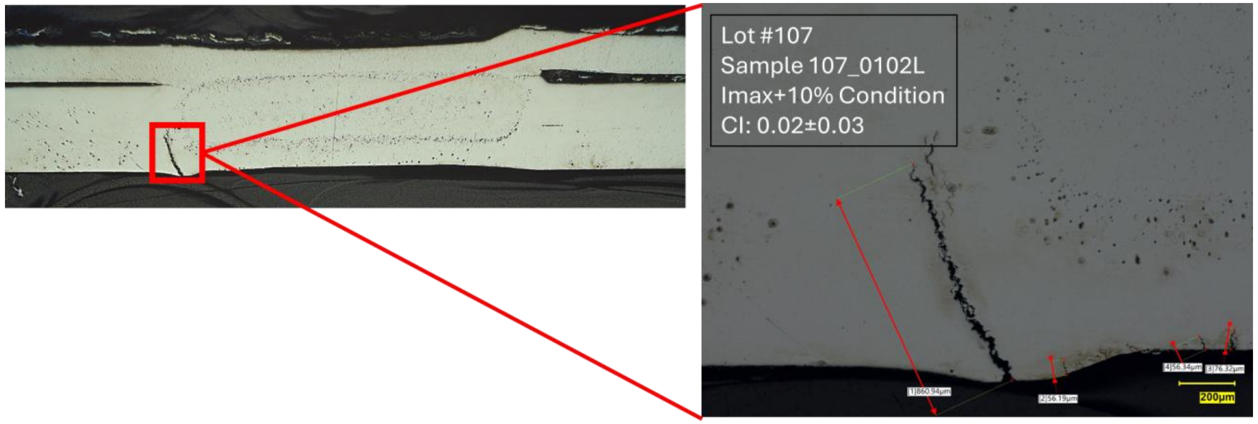
Mild
AHSS
← **Dissimilar stack-up**



Similar Stack-up



Dissimilar Stack-up



Conclusion of Task 1

- Using a Hierarchical evaluation process the following criteria were developed to results in the most industrially relevant LME characterization and testing methods:

	Type of metric	Definition of metric	Characterization method
LME characterization alternatives	Quantitative	Cracking index	Cross-sectioning

	stack-up	welding current		Electrode	Nugget size	No. of tests
LME testing alternatives	Similar two-sheet	Imax	Single-pulse	Based on a standard	Fixed	More than 10

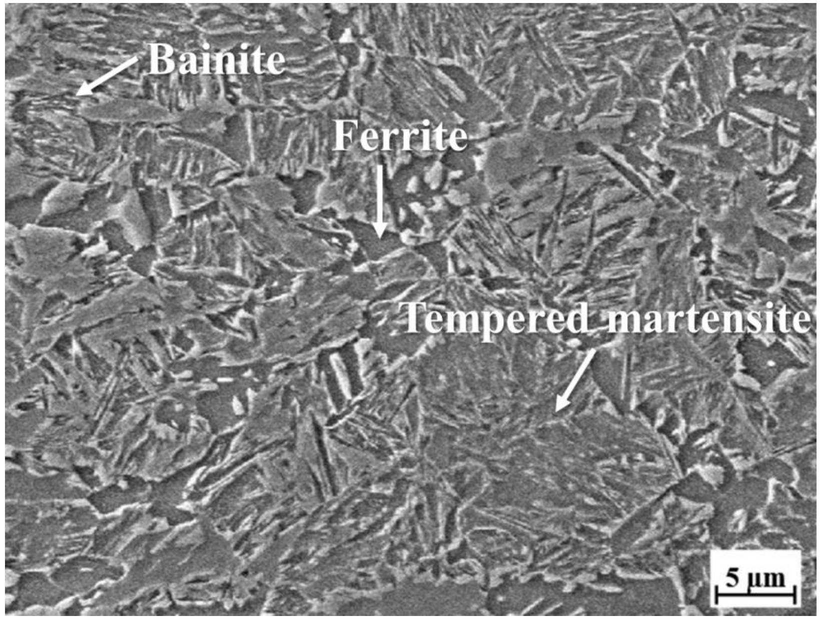
Characterization:

- Maximum crack length exhibited a strong correlation with TSS data, but only a weak and inconsistent correlation with CTS
- Crack frequency and average crack length showed no significant correlation with either TSS or CTS.
- Cracking index (CI) demonstrated the strongest correlation with both TTS and CTS results.

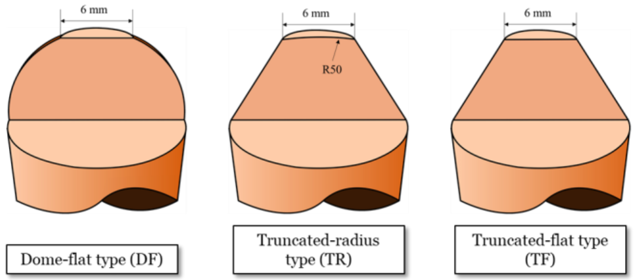
Testing:

- Testing similar joints at currently levels 10% above the expulsion current resulted in the highest LME response with low variability
  - In a high LME susceptible very small cracks (<50 μm) dominated so the dissimilar joints with long cracks had a lower CI value than the similar joints

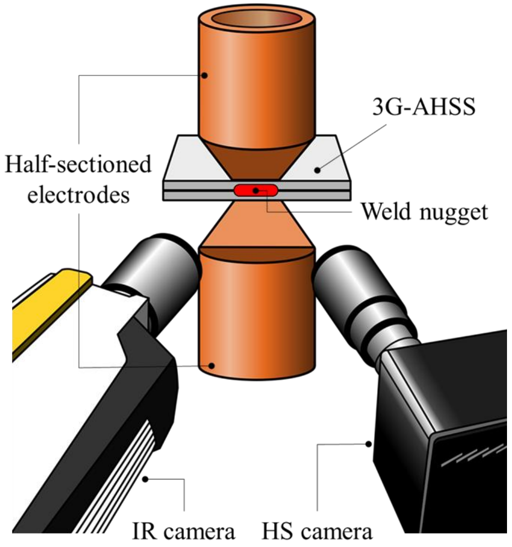
Investigated Materials and Setup for Welds



	C	Mn + Si	Ti+Mo+V+Nb	C_{eq}
GI- 980 3G-AHSS	**0.22**	**3.51**	**0.01**	**0.62**

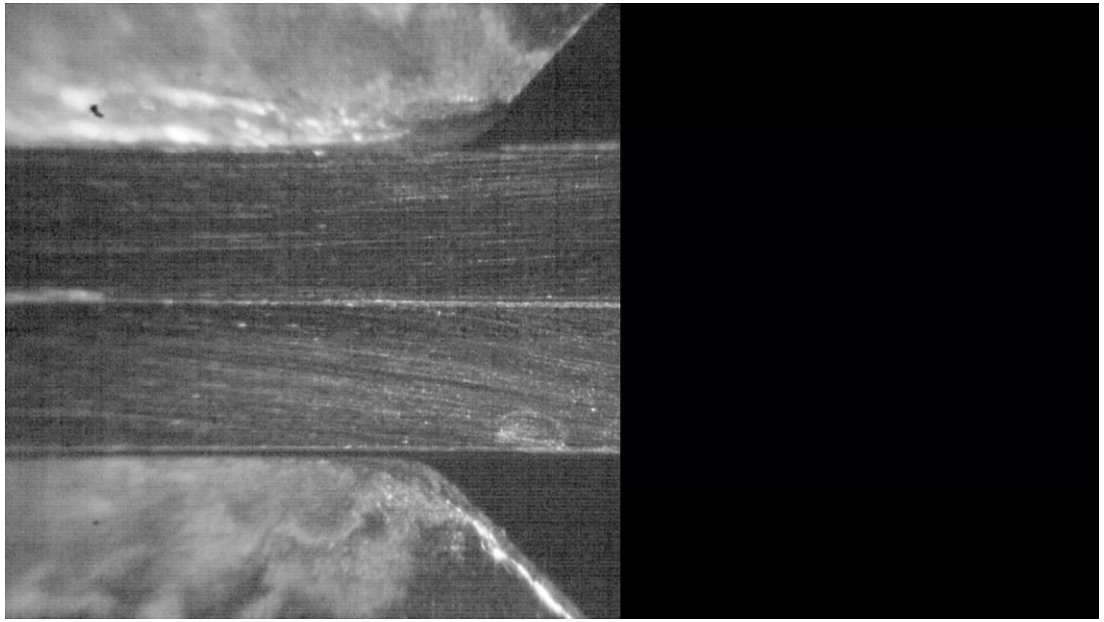


Schematic of H-RSW setup

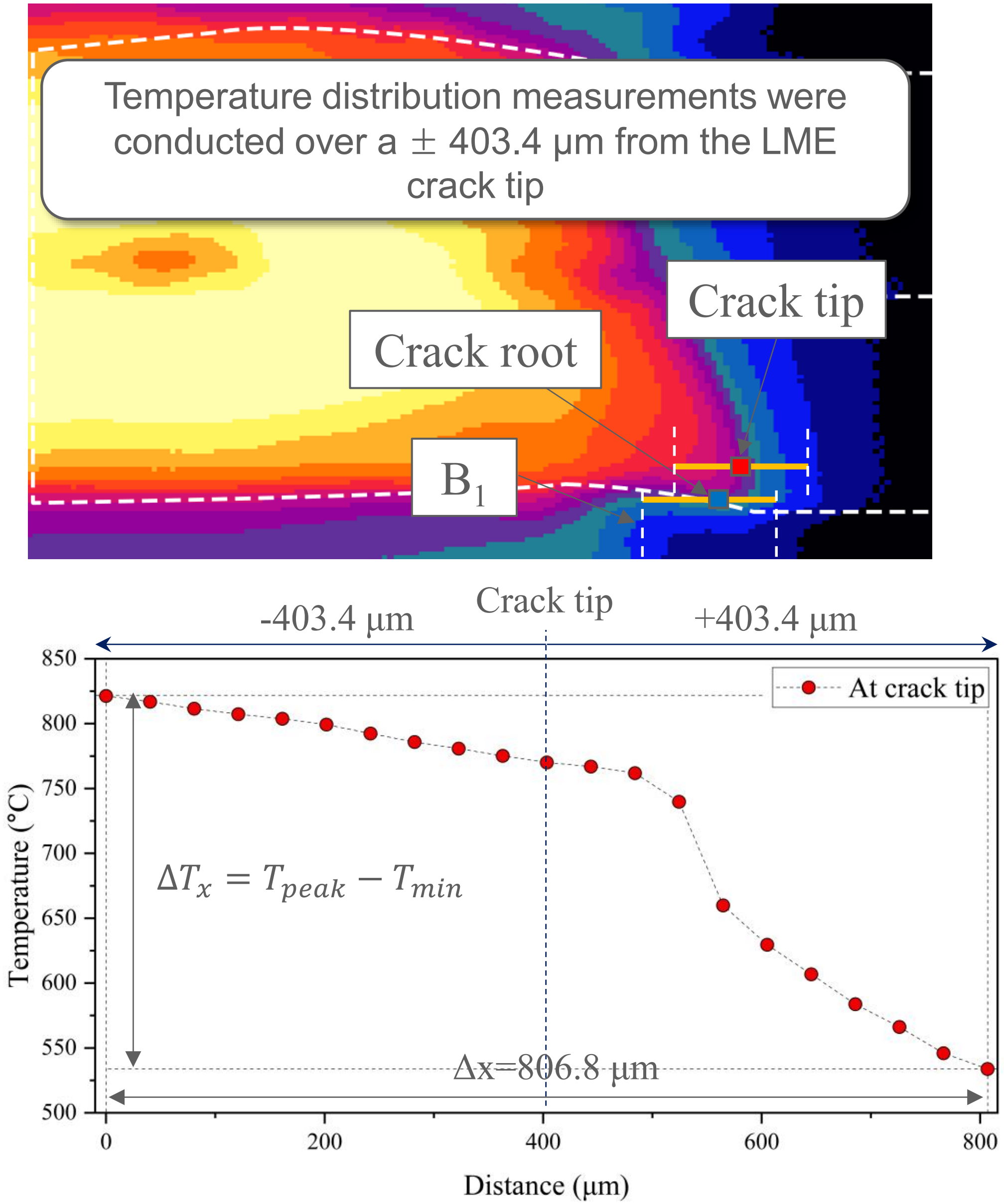


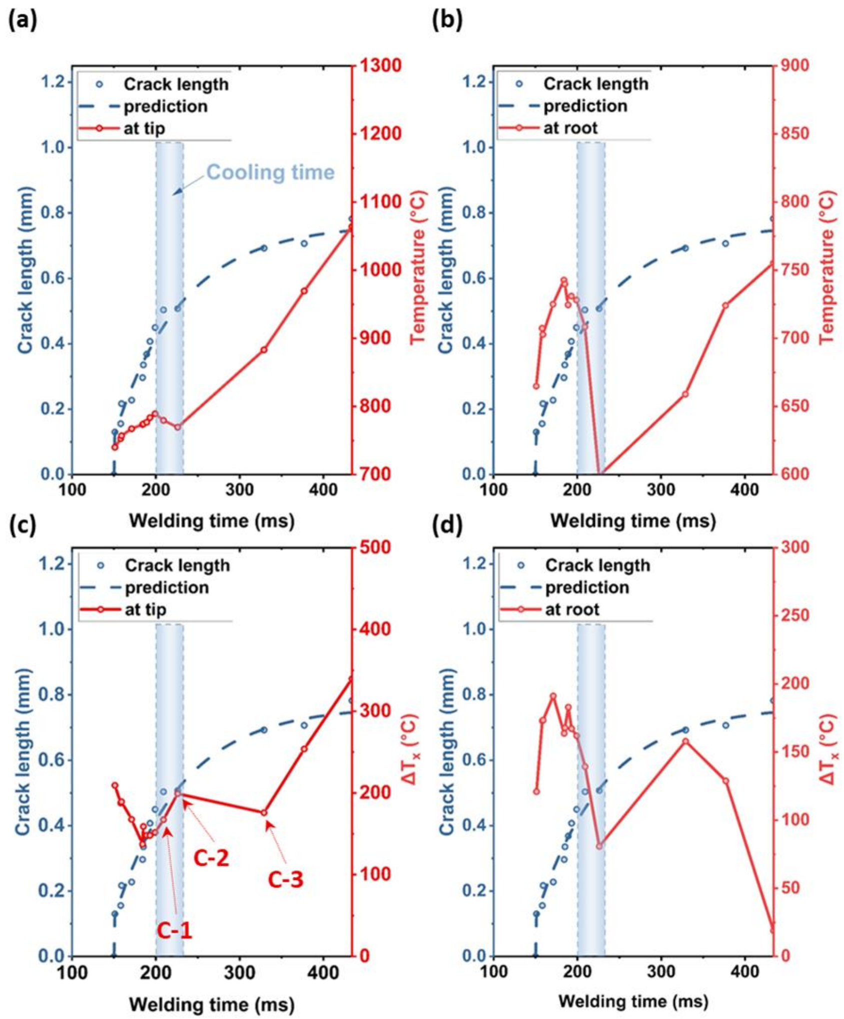
Half-sectioned welding parameter						
Electrode Force (kN)	Welding current (kA)	Squeeze time (ms)	Weld time (ms)	Hold time (ms)	Number of pulse	Cooling time between pulse (ms)
2.16	5.76	394	200	167	2	33

[Synchronized video]



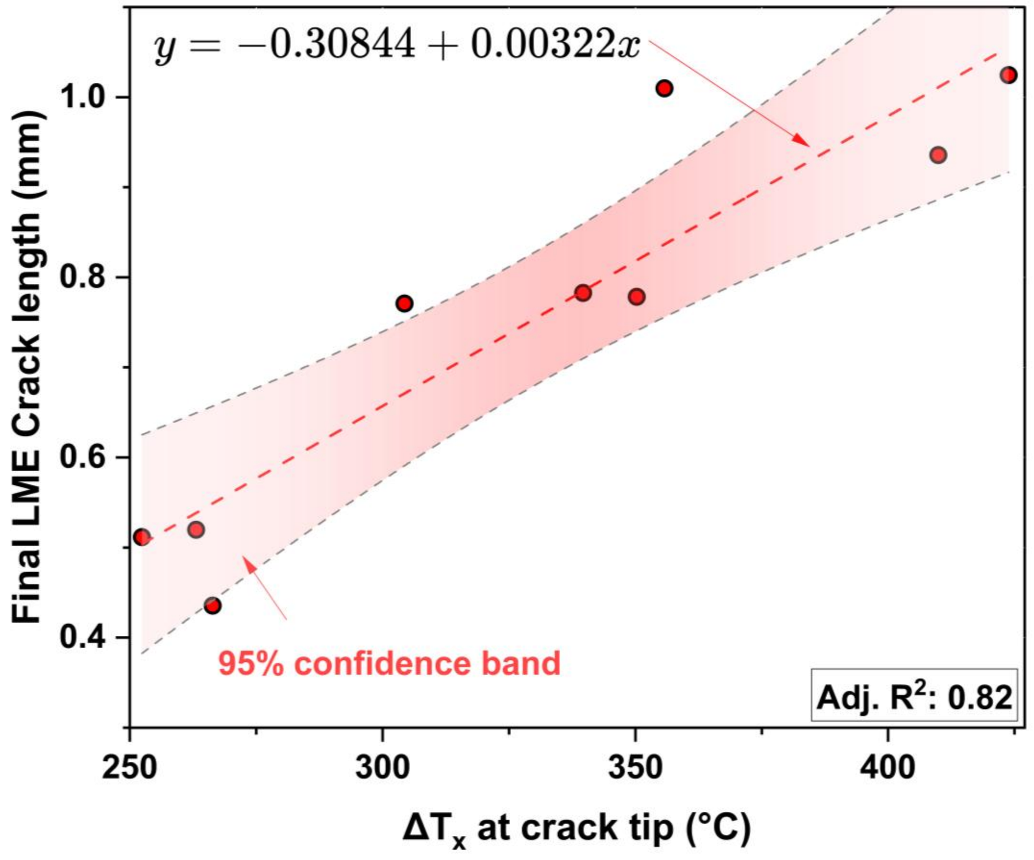
Methodology of Temperature Line Profile at Crack Tip





Prediction of LME Crack Length and Crack Growth Rate at Propagation Stage

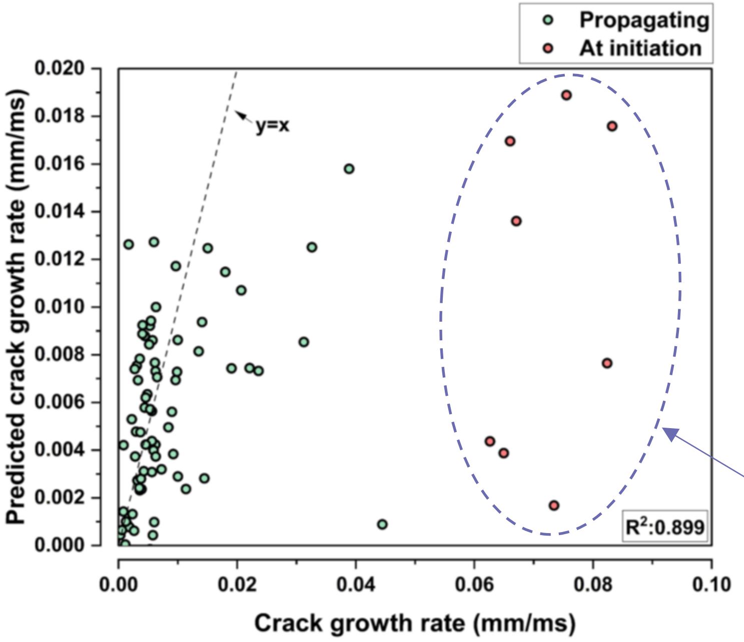
Final LME crack length can be predicted based on the ΔT_x at the tip



Prediction of LME Crack Length and Crack Growth Rate at Propagation Stage

LME crack growth rate during **propagation** model, developed through multiple linear regression analysis, provides factors that control LME crack growth

$$\frac{dL}{dt} = \underbrace{\beta_1 \cdot \left(\frac{dL}{dt}\right)_{t-1}}_{\text{Crack's own momentum}} + \overbrace{\beta_2 \cdot \Delta T_x}^{\text{Thermal stress at the crack tip}} - \underbrace{\beta_3 \cdot \left(\frac{dL}{dt}\right)_{t-1} \cdot \Delta t}_{\text{Damping effects at the crack tip}} - \overbrace{\beta_4 \cdot \Delta T_x \cdot L_{i,j}}^{\text{Gradual reduction of thermal stress}}$$

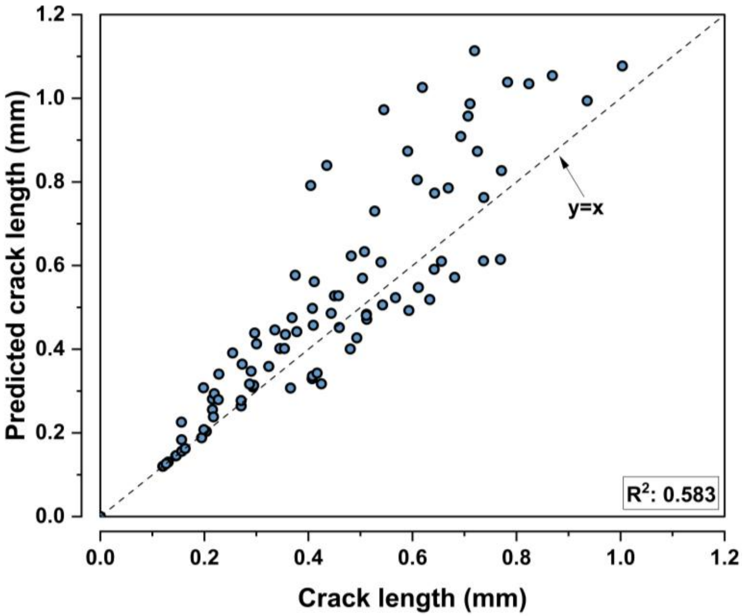


- β_x: Coefficient of each term.
- $\left(\frac{dL}{dt}\right)_{t-1}$: Crack growth rate at previous step.
- ΔT_x: Difference in temperature at crack tip.
- Δt: Change in time.
- $L_{i,j}$: Normalized LME crack length.

Data point related to the initiation stage

The LME crack length prediction model was developed using the LME crack growth rate model.

$$L = \underbrace{\left(\frac{dL}{dt}\right)_{t-1}}_{\text{predicted by the LME crack growth rate prediction model}} \cdot \Delta t + L_{t-1}$$



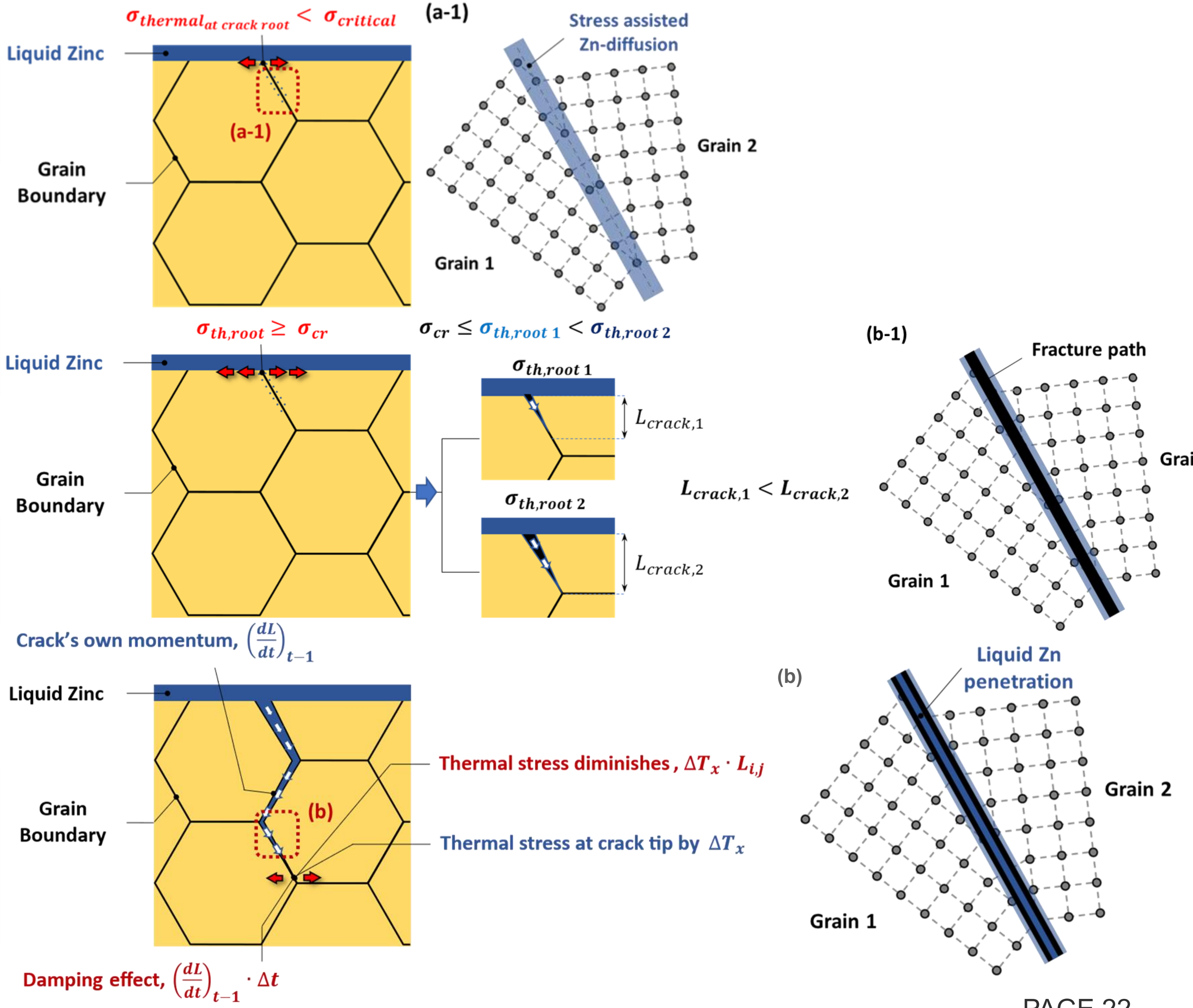
Summary of LME Crack Initiation and Propagation

ITD Phenomenon due to electrode collapse generates thermal stress. This thermal stress promotes the diffusion of zinc into grain boundary

When thermal stress at crack root exceeds the critical threshold, LME crack initiate

At initiation stage, higher thermal stress leads to a longer crack length, and the fracture path develops along weakened grain boundaries

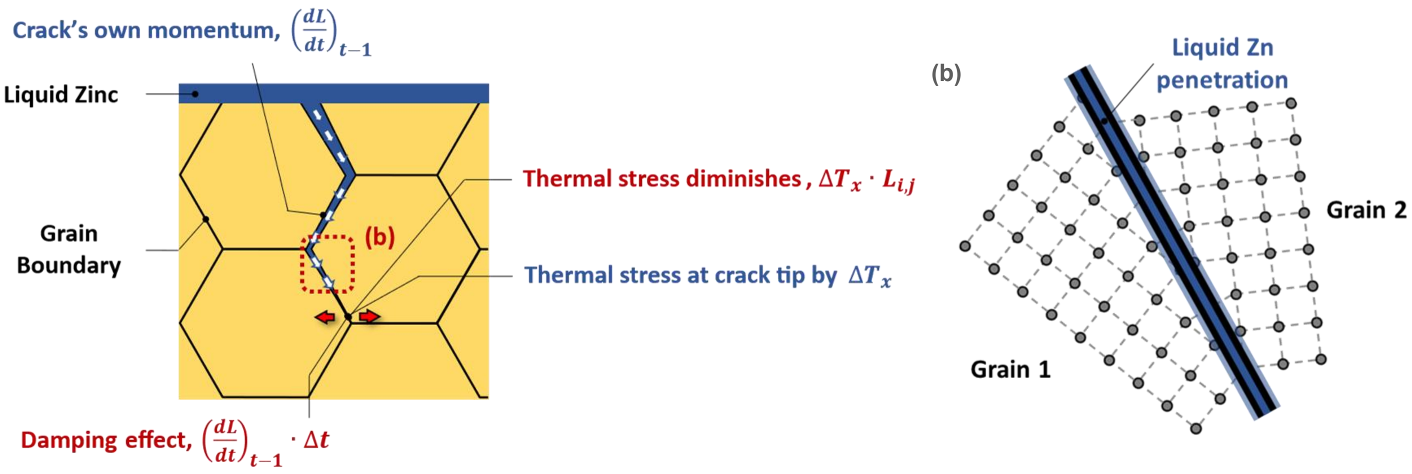
LME cracking behavior during propagation stage is characterized by four factors: the crack's own momentum, thermal stress at the crack tip, damping effect at the crack tip, and thermal stress reduction as the crack length increases



Conclusion of Task 2

This study used real-time monitoring of LME cracking during actual spot-welding to quantify LME cracking behavior. This approach allowed for the determination of LME crack propagation kinetics and the development of models to predict crack length and growth rate.

- LME crack propagation is governed by the combined action of **four key factors**: the crack's momentum, thermal stress at the crack tip, damping effects at the crack tip, and gradual reduction of thermal stress as the crack length increases.



Thanks for your attention!