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FWP-B100-19010

Multi-pass Hybrid Laser Arc Welding of Alloy 740H

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Co-investigator: Todd Palmer (Penn State)

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Battelle Energy Alliance manages INL for the U.S. Department of Energy's Office of Nuclear Energy

INL Idaho National Laboratory

Background

- Alloy 740H identified for the a-USC fossil fuel plant

Nominal Chemical Composition (wt%)									
C	**Mn**	**Fe**	**S**	**Si**	**Cu**	**Ni**	**Cr**	**Al**	**Ti**
0.034	0.29	0.19	0.0008	0.15	0.02	Rem.	24.57	1.39	1.45
Co	**Mo**	**Nb**	**Ta**	**P**	**B**	**V**	**W**	**Zr**	**Other**
20.07	0.49	1.46	0.007	0.008	0.0013	0.008	0.05	0.03	<0.1

- Thick section joining issues:
  - Gas Tungsten Arc Welding – best properties, slow
  - Gas Metal Arc Welding – Weld Strength Reduction Factor: 0.70
  - Submerged Arc Welding (SAW) – no flux has been developed

Approach

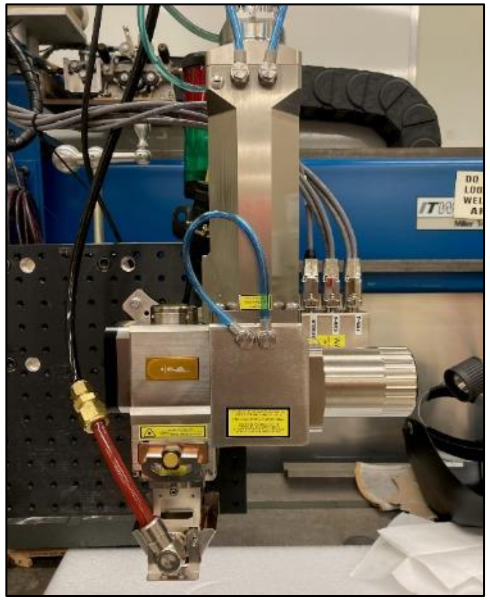
Objective:

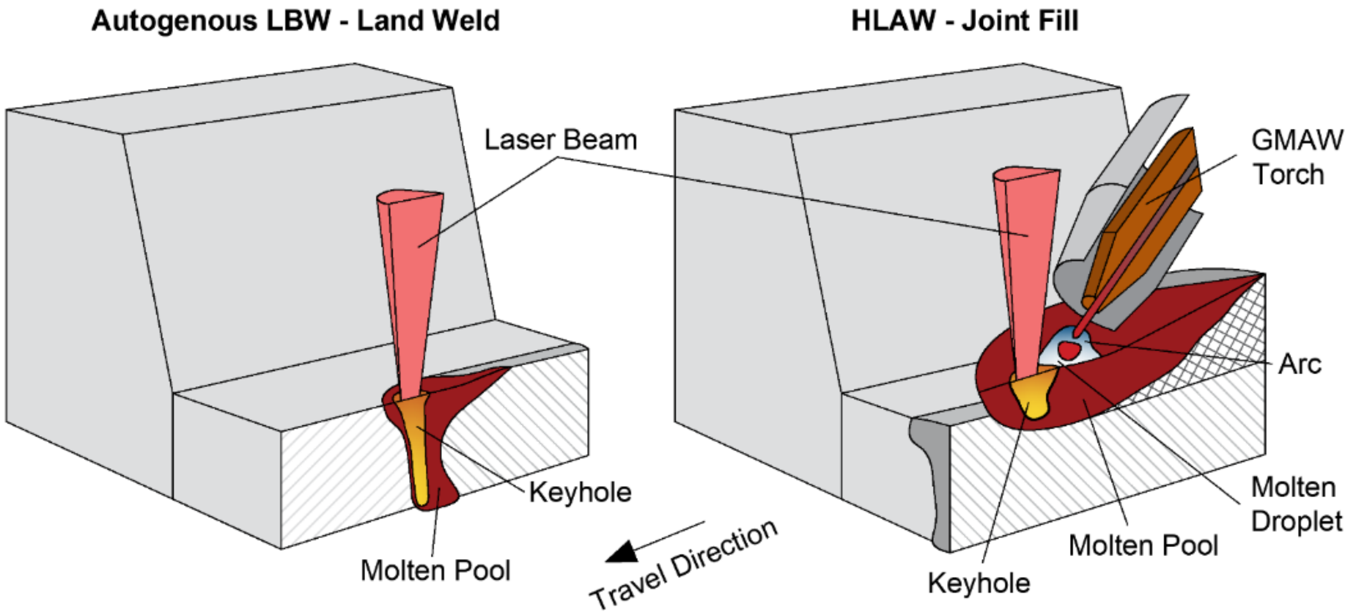
Reduce joining time by a factor of 2 while retaining or improving high temperature properties

- Strategies:
  - Deep penetration laser welding of thick weld groove lands (~12.7 mm)
    - reduce weld volume
  - Increase welding speed using Hybrid Laser Arc Welding (HLAW)
    - reduce arc time
  - Narrow groove design
    - reduce weld volume (76.2 mm thick plates/pipes)
  - Incorporate laser wobble
    - improve microstructure and improve Weld Strength Reduction Factor (WSRF)

Laser Wobble

- PSU – laser weld 12.7 mm thick weld groove land (10 kW laser)
- INL – hybrid laser arc welding (HLAW) of weld joint (4 kW laser)
  - Utilize laser to improve arc stabilization and laser wobble for defect reduction at increased travel speed

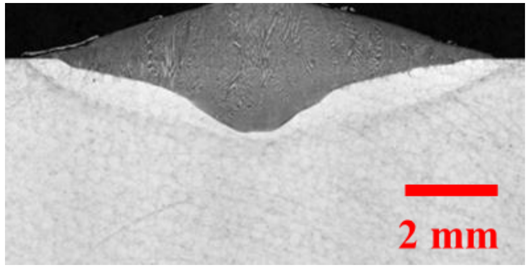




Task 1: Deep Penetration Land Welding (Penn State)

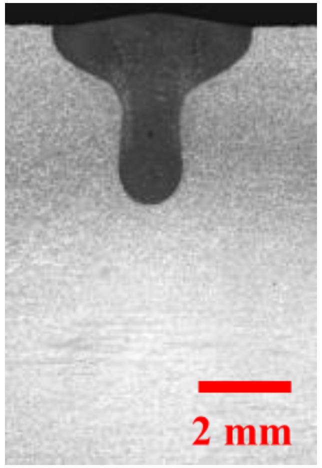
High Laser Powers Improve Penetration

High power laser welding can improve welding efficiency by achieving weld pool depth on the order of 10 mm in a single pass.

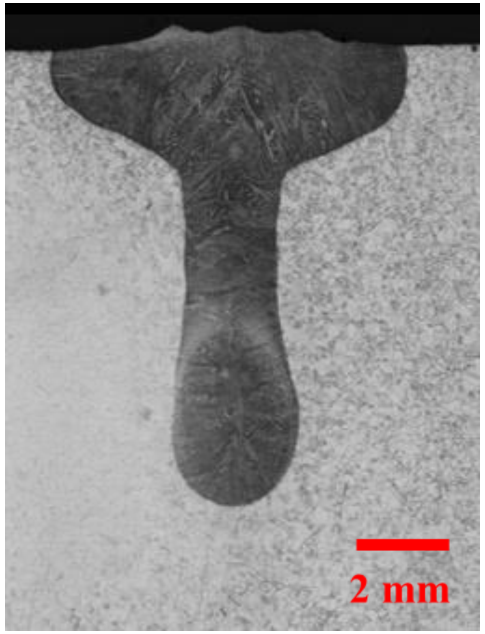


Inconel 740H

Arc: 200A, 28 V Laser: 1 kW
Welding speed: 16.9 mm/s
Penetration: 1.7 mm



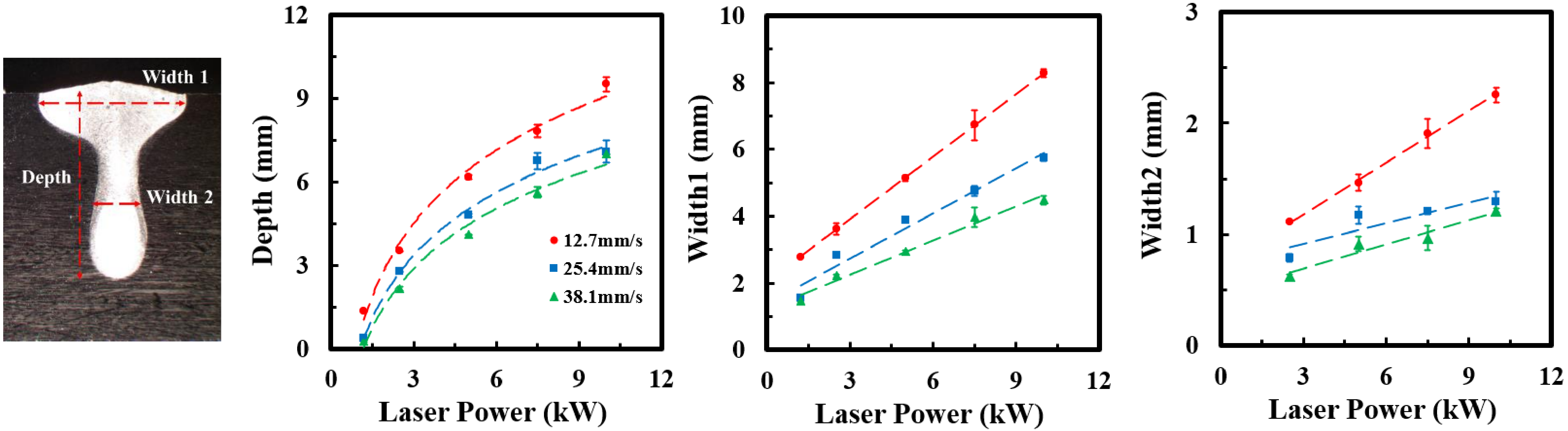
Laser power: 2.5 kW
Welding speed: 12.7 mm/s
Penetration: 3.8 mm



Laser power: 10 kW
Welding speed: 12.7 mm/s
Penetration: 9.5 mm

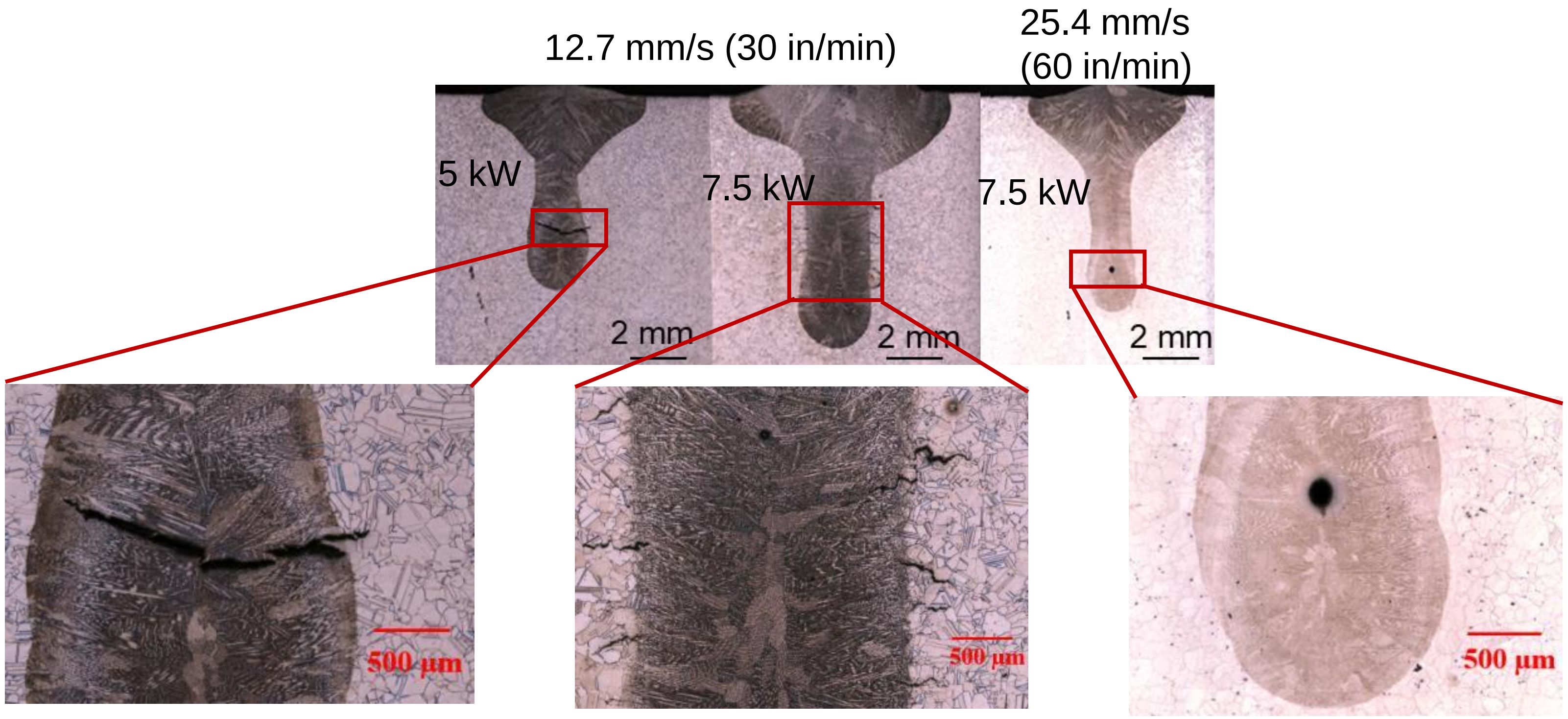
Process Variables Impacted Weld Dimensions

Weld pool dimensions, such as weld depth, width, and keyhole width, were measured on multiple weld cross sections under different processing conditions for Inconel 740H.



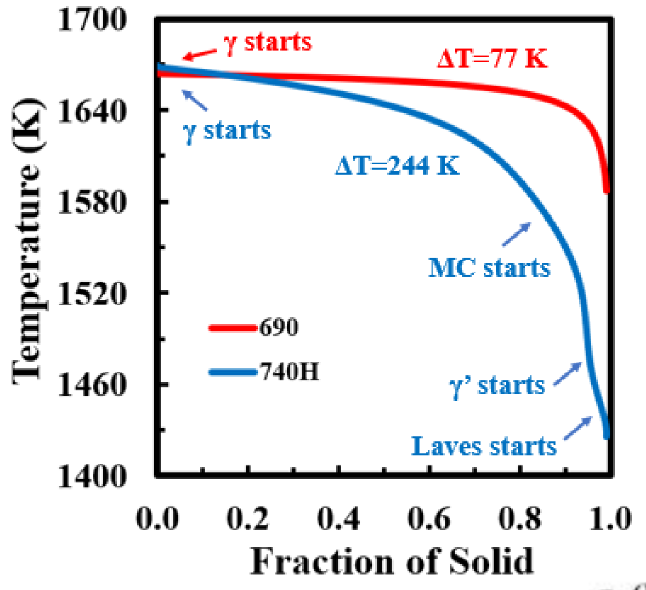
Linear Laser Welding Defects

- Horizontal intergranular solidification cracks observed in fusion zone
- Multiple liquation cracks observed in the HAZ
- Keyhole collapse porosity present near the bottom of the keyhole



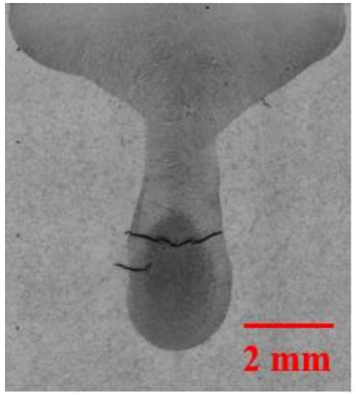
Integrated Modeling of Solidification Cracking

Alloy Composition

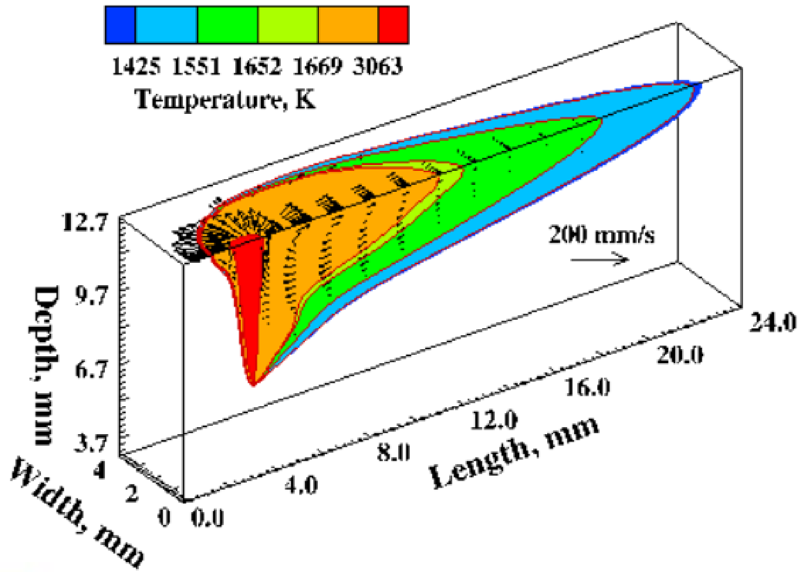


Scheil Simulation

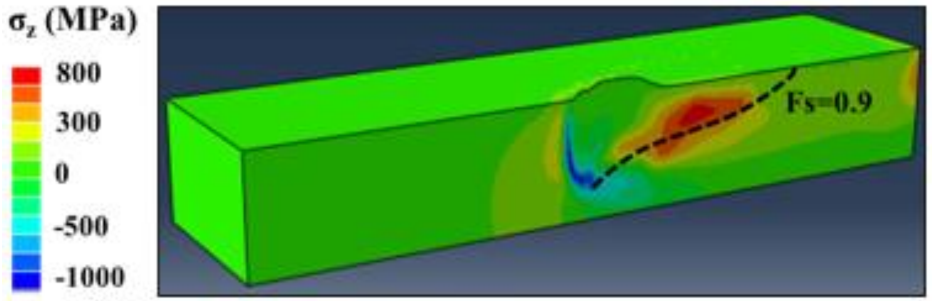
Solidification cracking



Process Conditions



Stress State



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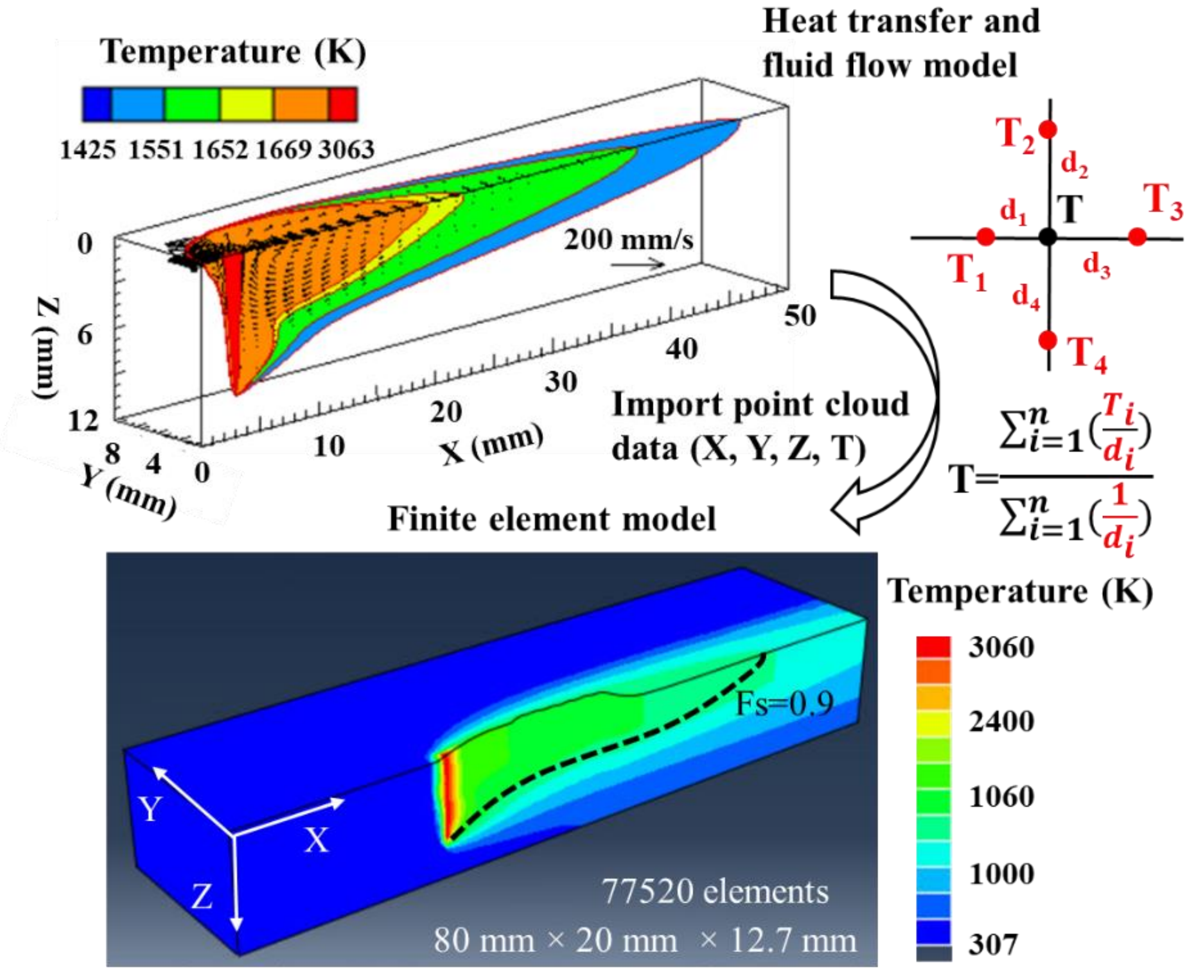
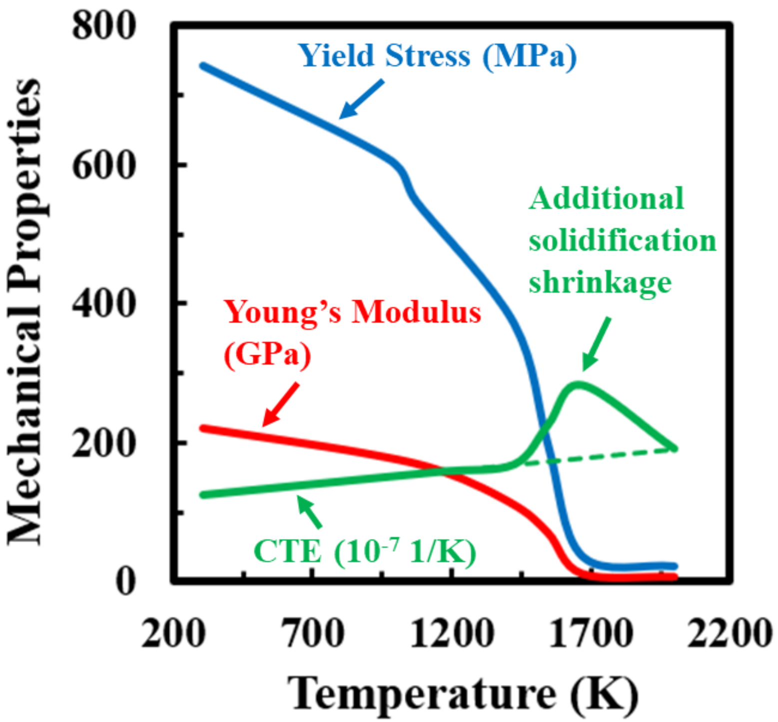
Coupling of Thermal and Mechanical Models



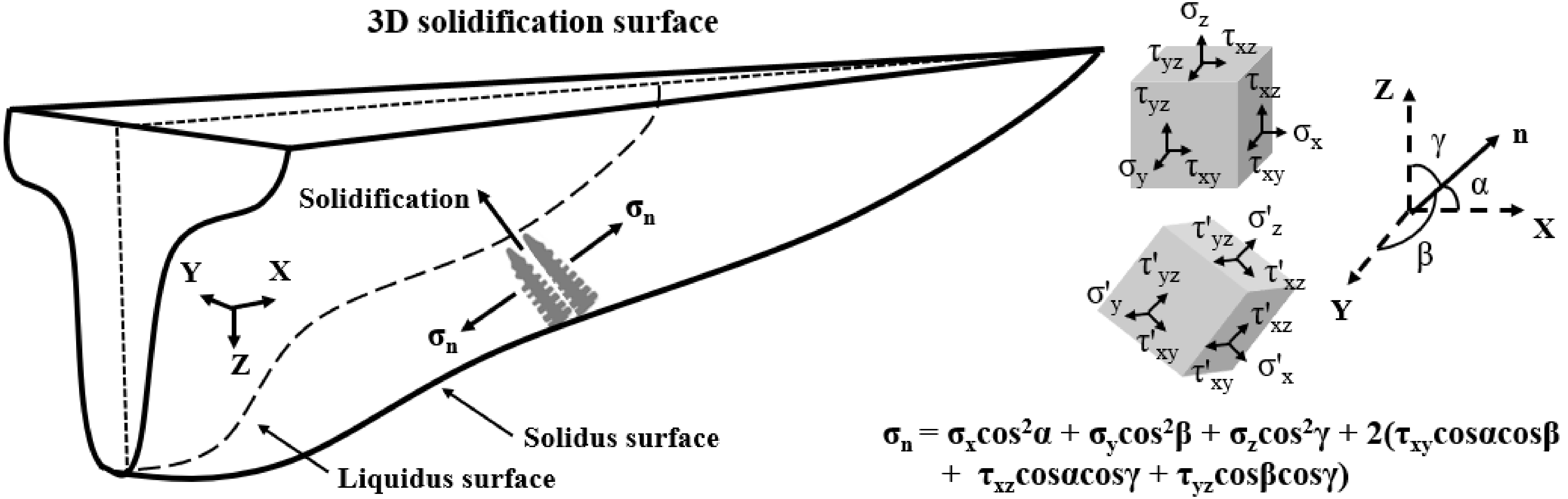
Temperature dependent properties



https://www.specialmetals.com/documents/technical-bulletins/inconel/inconel-alloy-740h.pdf

Three-Dimensional Stress State Transformation

Stress transformation was performed to calculate the stress state normal to the solidification direction, which follows the principle heat flow direction.



$$\sigma_n = \sigma_x \cos^2\alpha + \sigma_y \cos^2\beta + \sigma_z \cos^2\gamma + 2(\tau_{xy}\cos\alpha\cos\beta + \tau_{xz}\cos\alpha\cos\gamma + \tau_{yz}\cos\beta\cos\gamma)$$

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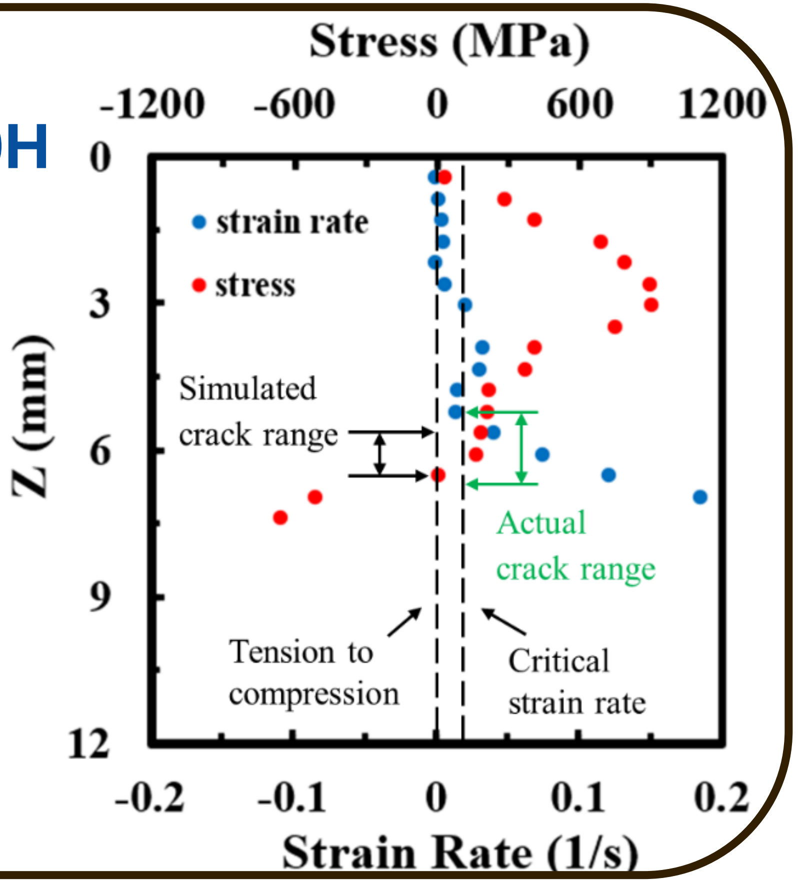
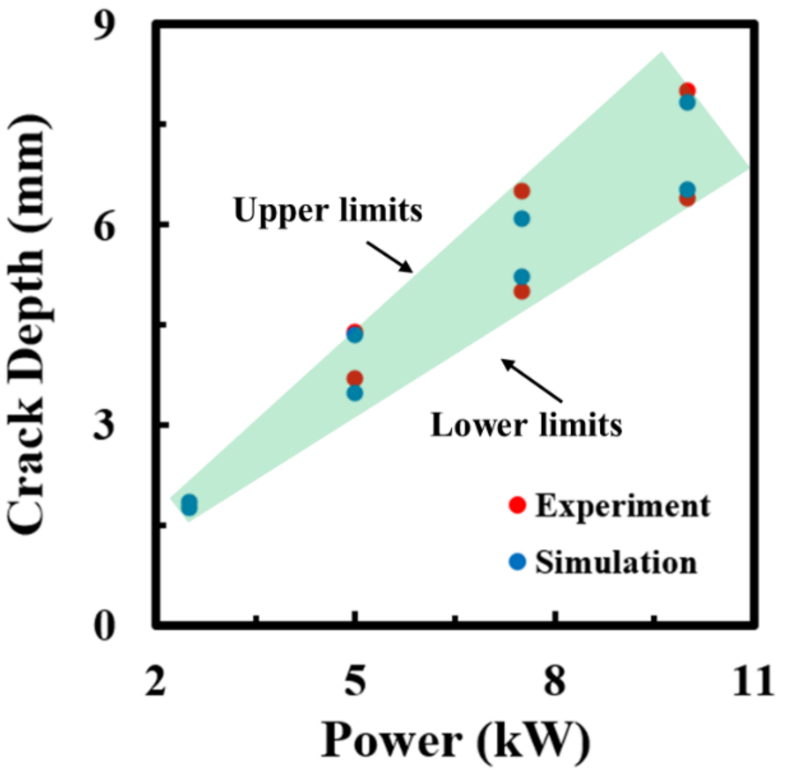
Stress and Strain Rate Drives Cracking

Solidification cracking is likely to occur where sufficiently high strain rate and tensile stress are both present.

Inconel 740H

With high strain rate and tensile stress both present, the crack range is around 0.9 mm





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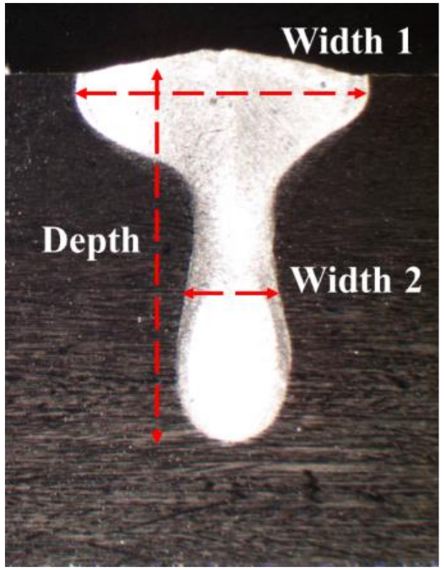
Comparison of Linear and Wobble Welds

- Wobble welds with 0.4 mm amplitude have comparable depths as linear welds
- Wobble welds with 1.6 mm amplitude have smaller pool depth than linear welds
- Wobble frequency does not significantly change the pool depth

12.7 mm/s welding speed

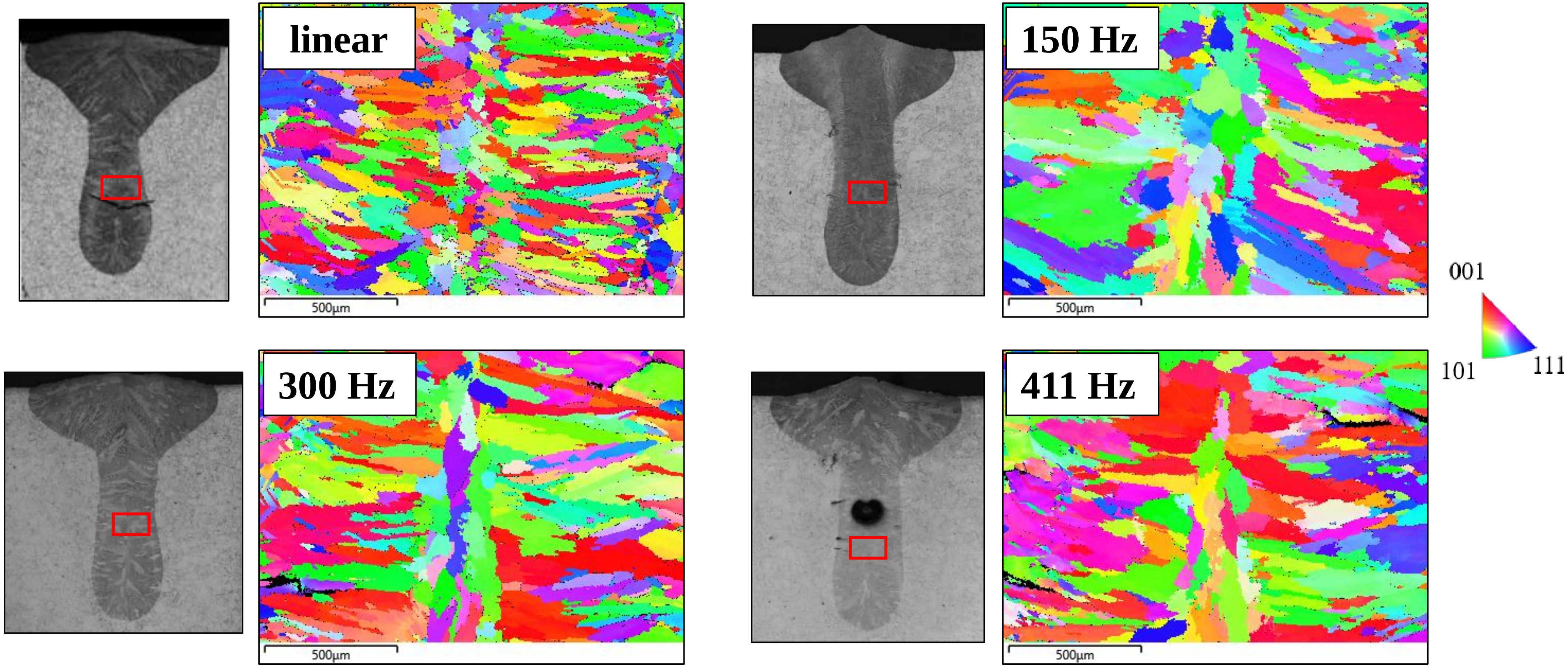


Amplitude (mm)	Frequency (Hz)	Depth (mm)	Width 1(mm)	Width 2 (mm)
5 kW				
None	None	6.2 ± 0.1	5.1 ± 0.1	1.4 ± 0.1
0.4	150	6.5 ± 0.1	4.9 ± 0.1	1.8 ± 0.1
0.4	300	6.5 ± 0.1	5.1 ± 0.1	1.6 ± 0.1
0.4	411	6.4 ± 0.1	5.4 ± 0.2	1.7 ± 0.1
1.6	150	4.3 ± 0.2	6.4 ± 0.2	2.6 ± 0.1
1.6	300	3.9 ± 0.1	6.2 ± 0.1	2.5 ± 0.1
1.6	411	4.0 ± 0.1	5.9 ± 0.1	2.6 ± 0.1
7.5 kW				
None	None	7.8 ± 0.2	6.7 ± 0.4	1.8 ± 0.1
0.4	150	7.8 ± 0.1	6.6 ± 0.1	2.0 ± 0.1
0.4	300	8.0 ± 0.1	6.7 ± 0.1	2.0 ± 0.1
0.4	411	7.7 ± 0.1	7.0 ± 0.1	2.3 ± 0.1
1.6	150	6.9 ± 0.1	8.0 ± 0.1	3.1 ± 0.1
1.6	300	6.7 ± 0.1	6.7 ± 0.1	3.3 ± 0.1
1.6	411	6.5 ± 0.1	6.2 ± 0.1	3.3 ± 0.1
10 kW				
None	None	9.5 ± 0.3	8.2 ± 0.1	2.2 ± 0.1
0.4	150	10.0 ± 0.1	6.8 ± 0.1	2.5 ± 0.1
0.4	300	9.8 ± 0.2	8.1 ± 0.1	2.6 ± 0.1
0.4	411	9.6 ± 0.1	8.1 ± 0.1	2.5 ± 0.1
1.6	150	8.2 ± 0.1	8.3 ± 0.1	3.4 ± 0.2
1.6	300	8.5 ± 0.1	6.6 ± 0.1	3.5 ± 0.2
1.6	411	8.7 ± 0.2	5.9 ± 0.1	3.7 ± 0.1

Wobble Weld Grain Structure

Wobble welds with small amplitude displayed similar grain structure as linear welds

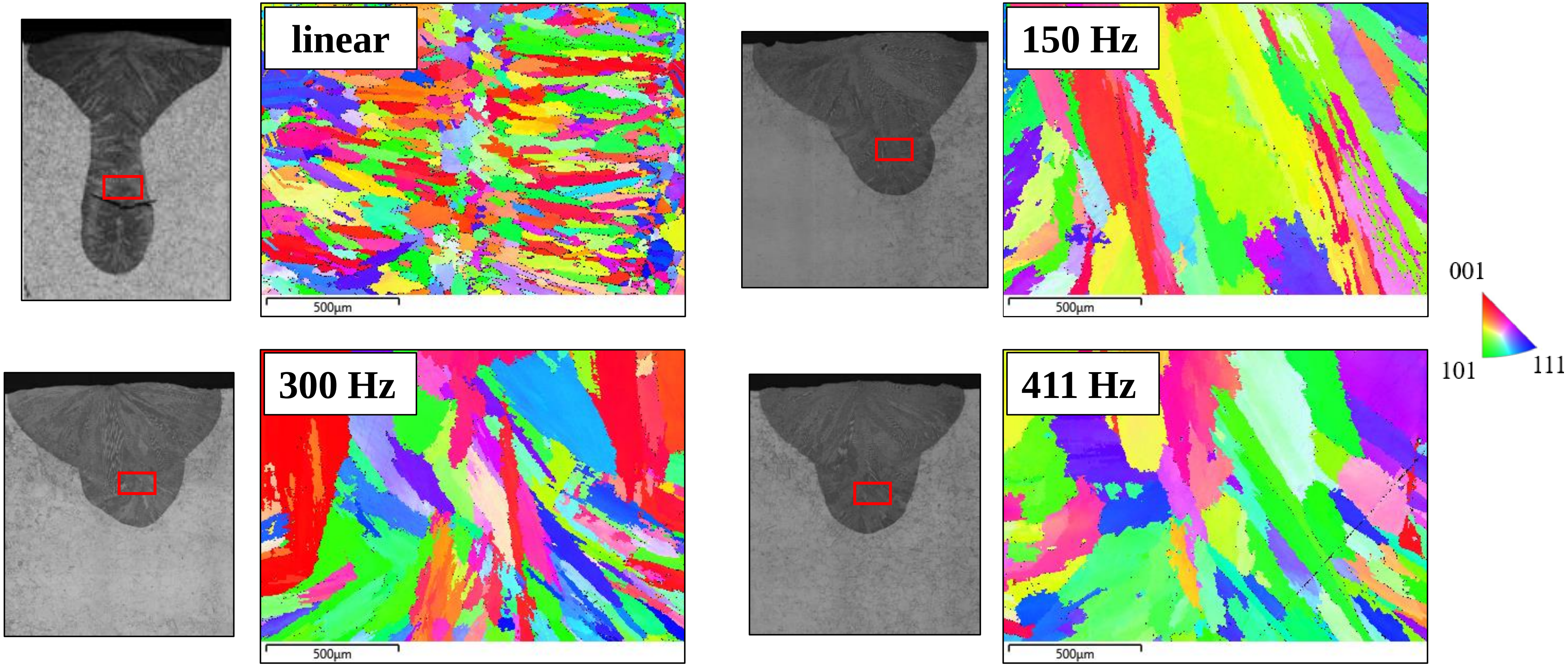
5 kW
12.7 mm/s
Amplitude
0.4 mm



Wobble Weld Grain Structure

Wobble welds with large amplitude displayed randomly oriented grain structure.

5 kW
12.7 mm/s
Amplitude
1.6 mm



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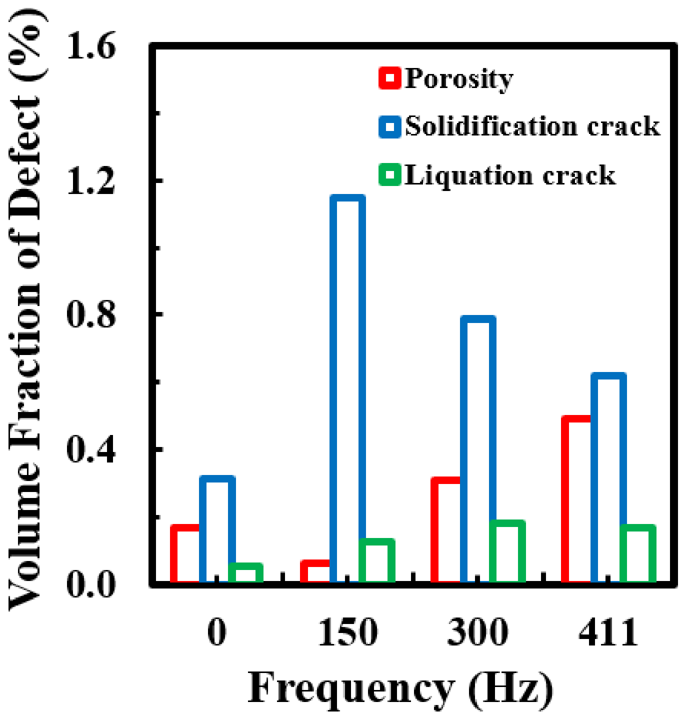
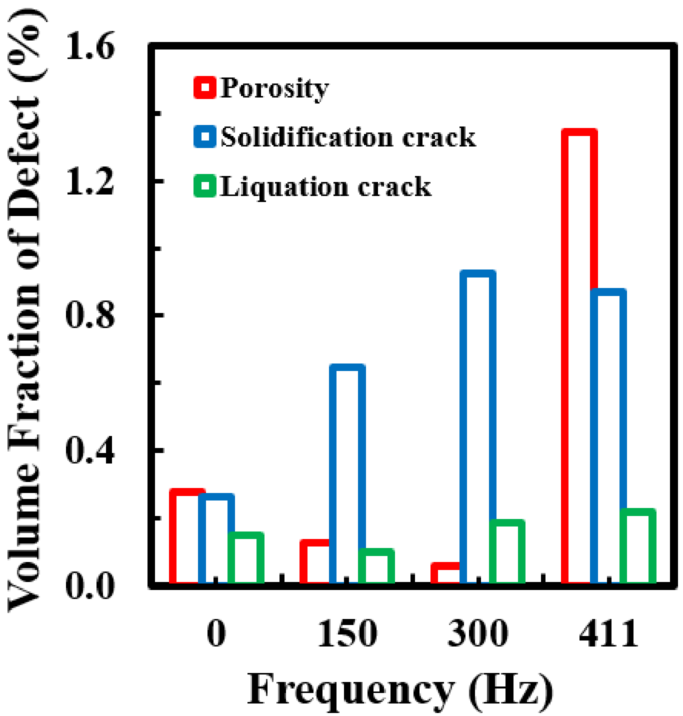
Defects in Linear and Wobble Welds

Welding speed of 12.7 mm/s and wobble amplitude of 0.4 mm

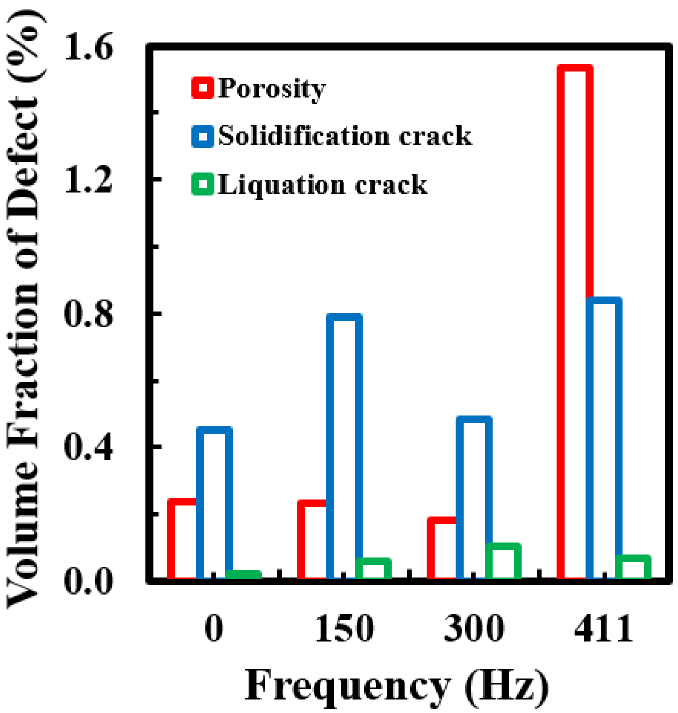
5 kW



7.5 kW



10 kW



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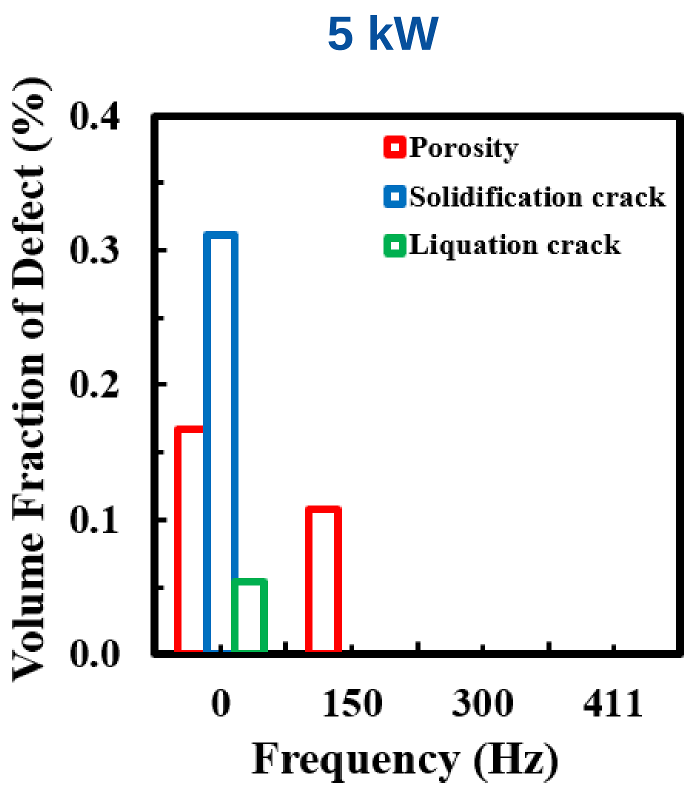
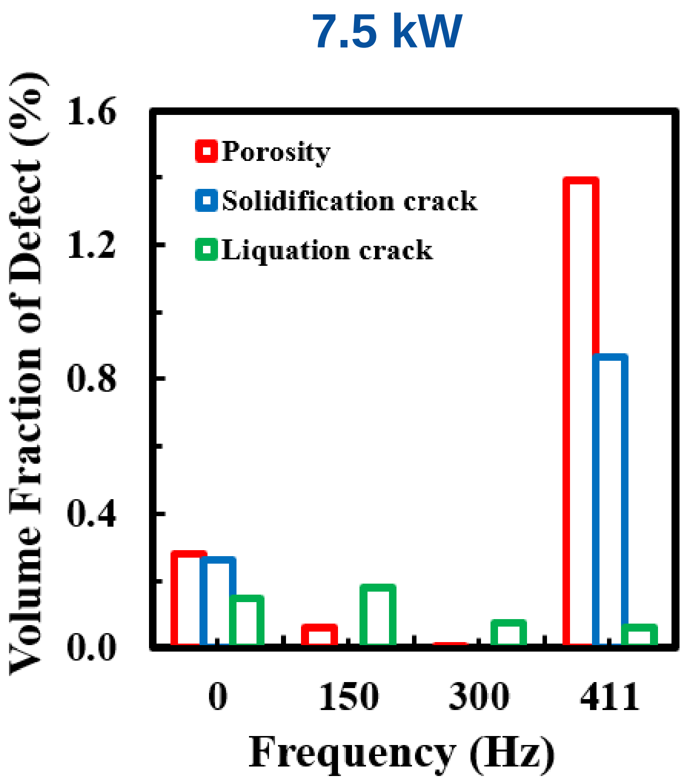
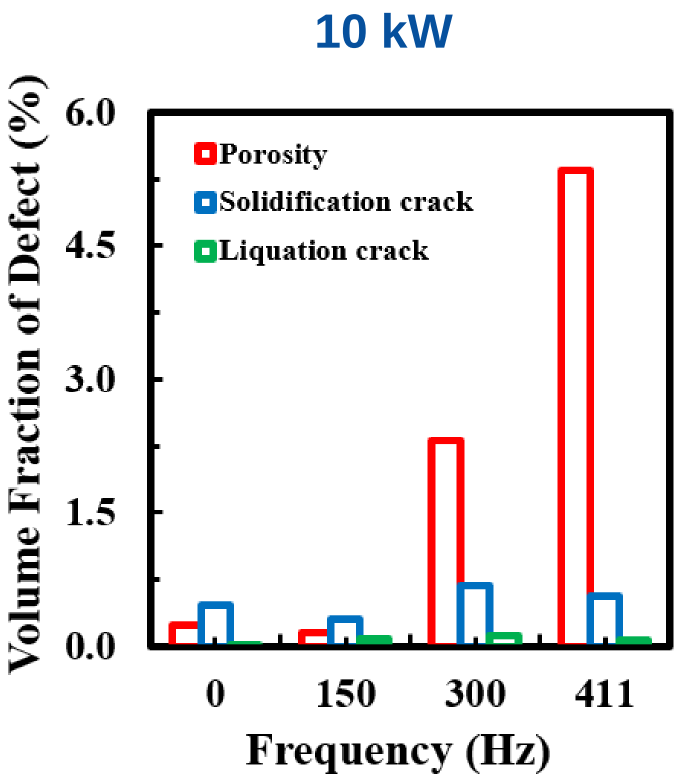
Defects in Linear and Wobble Welds

Welding speed of 12.7 mm/s and wobble amplitude of 1.6 mm







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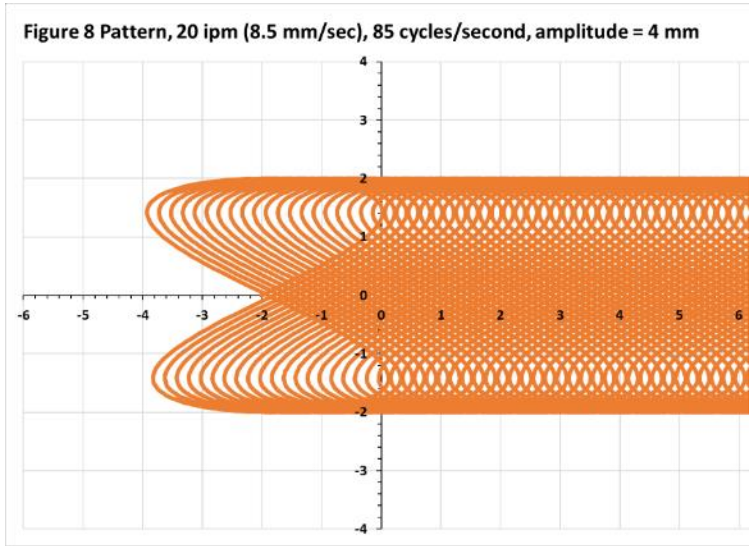
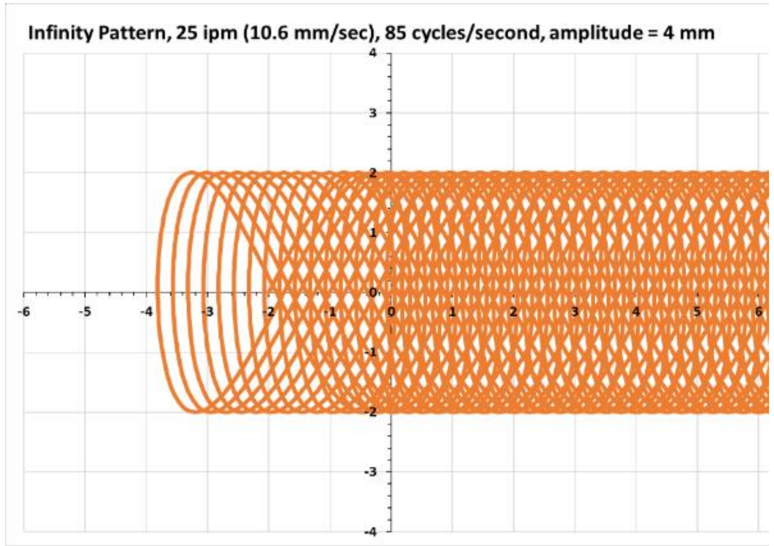
Task 2: HLAW Groove Filling (INL)

HLAW Groove Filling





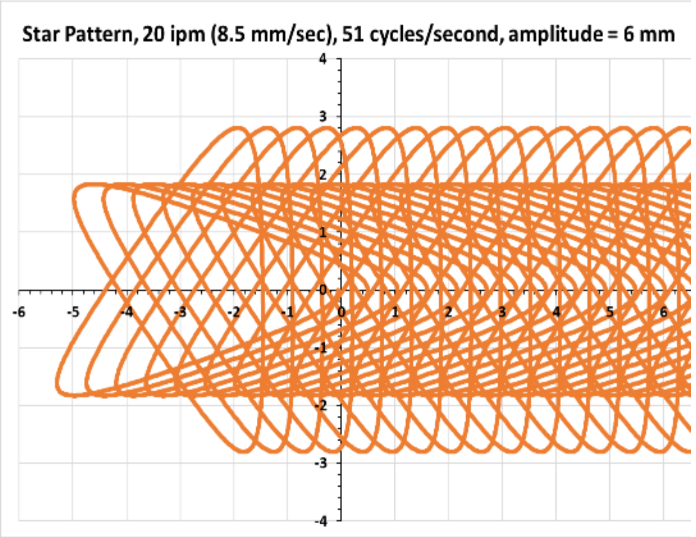
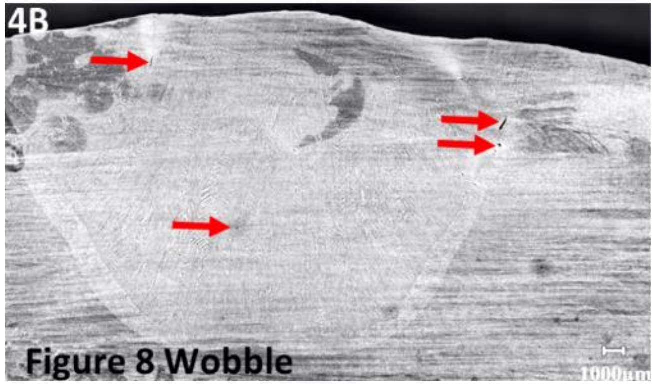
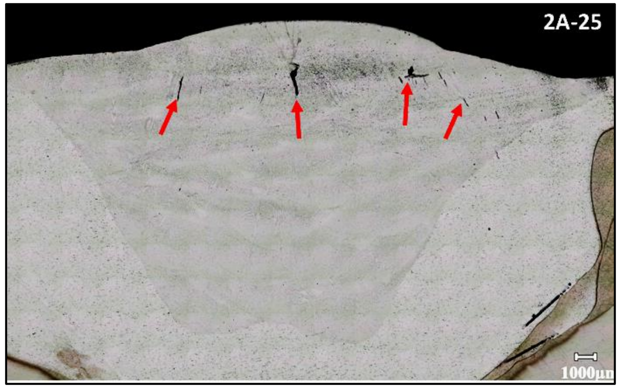


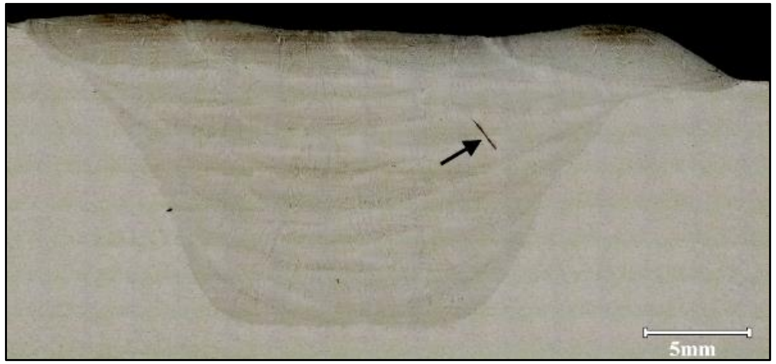
Figure 8 Wobble

Infinity Wobble

Star Wobble







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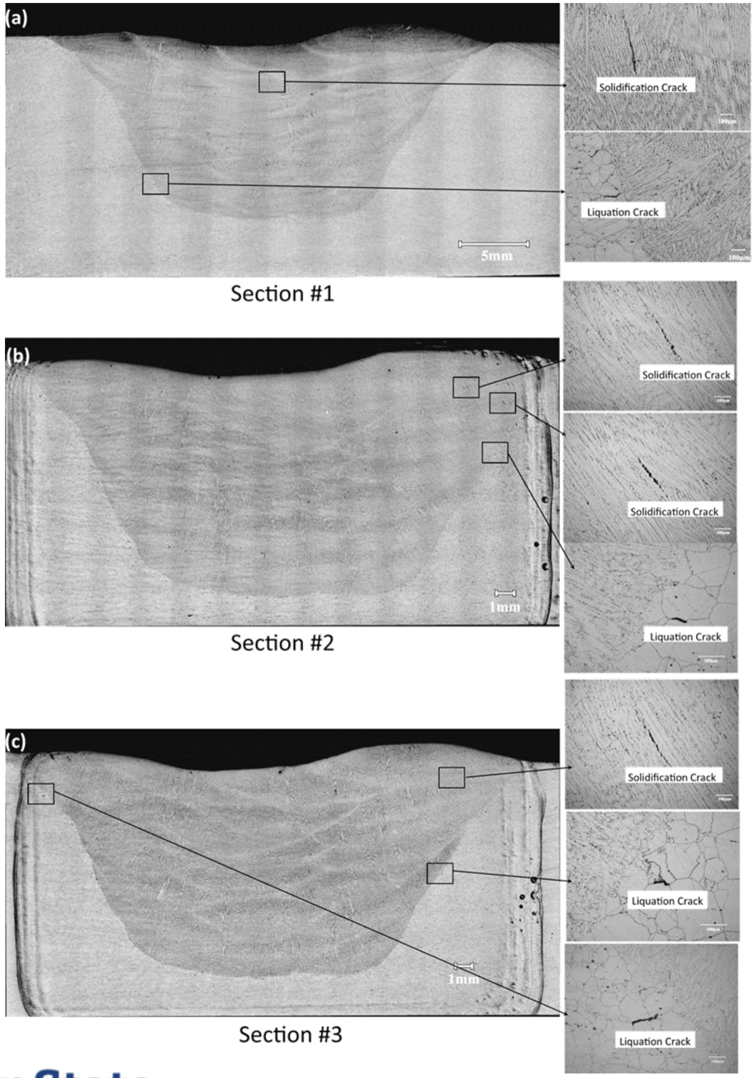
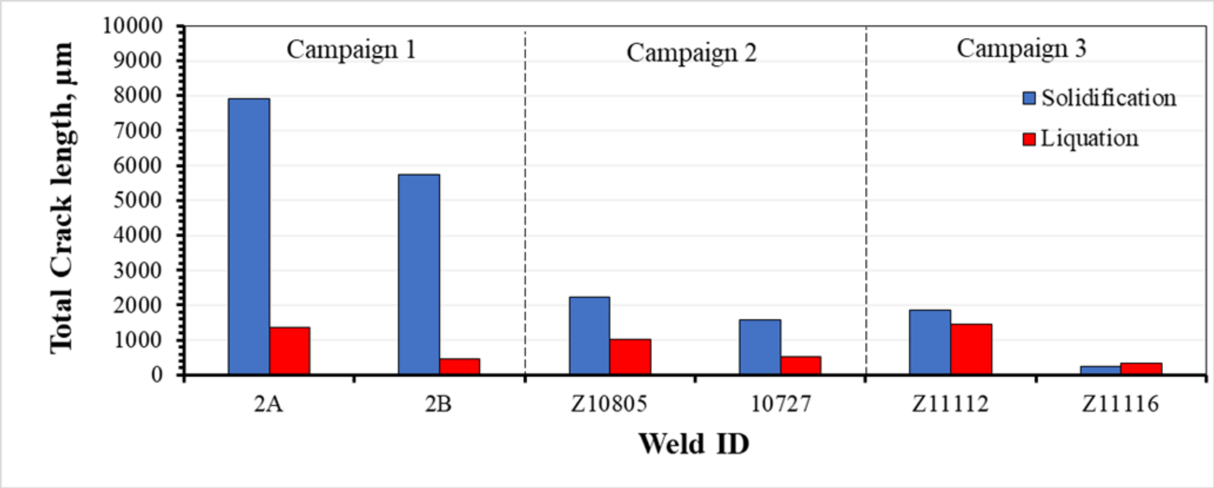
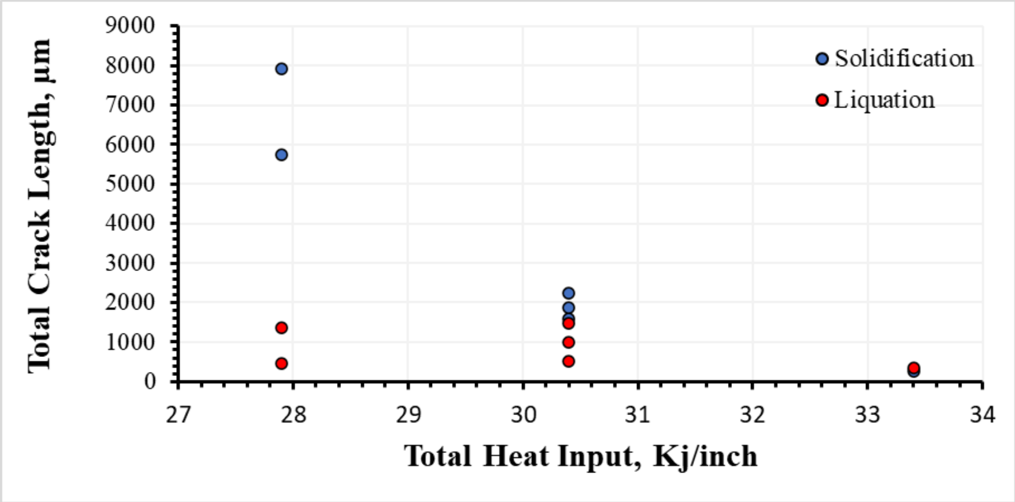
HLAW Groove Filling







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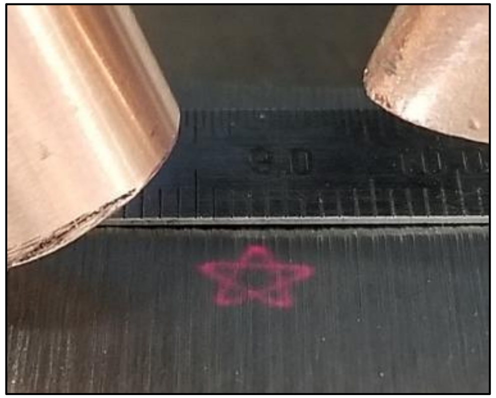
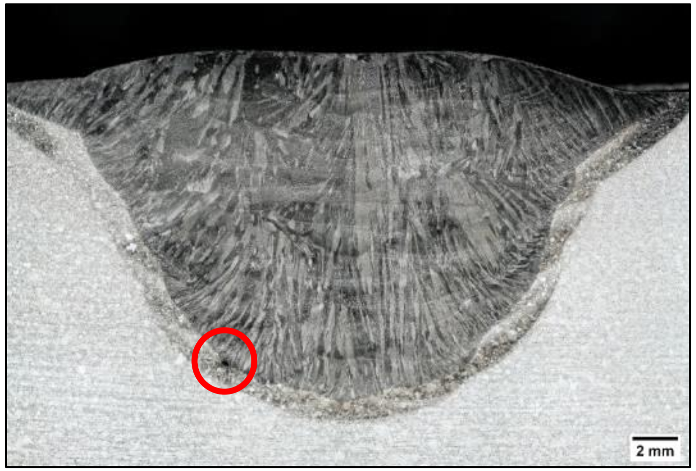
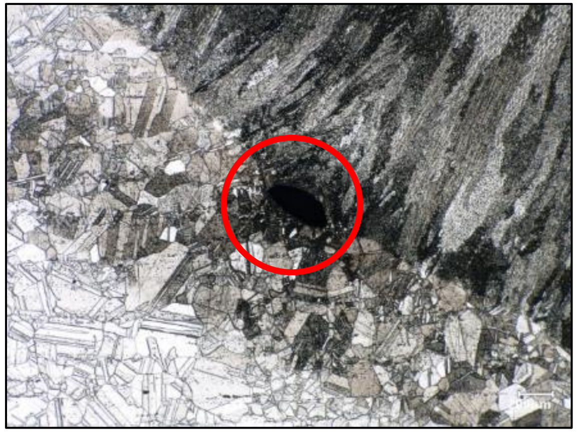
HLAW Groove Filling

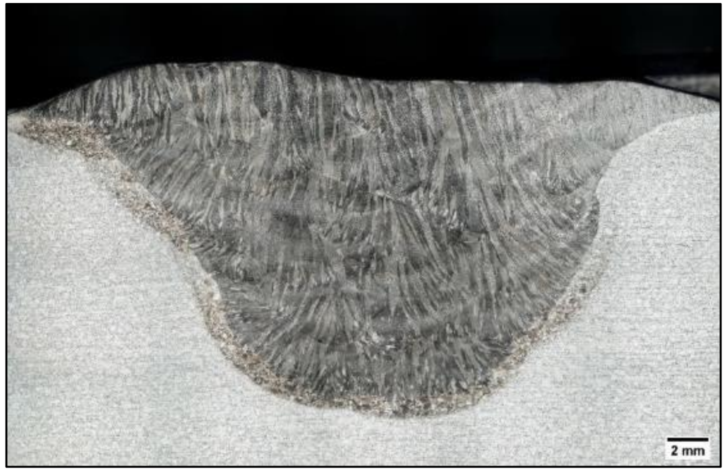


2 kW laser power

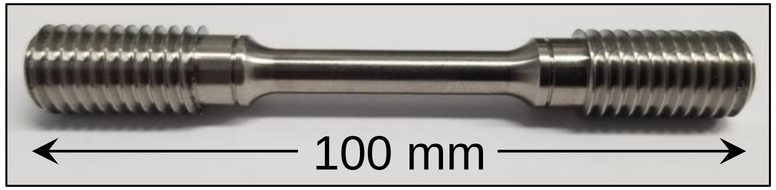


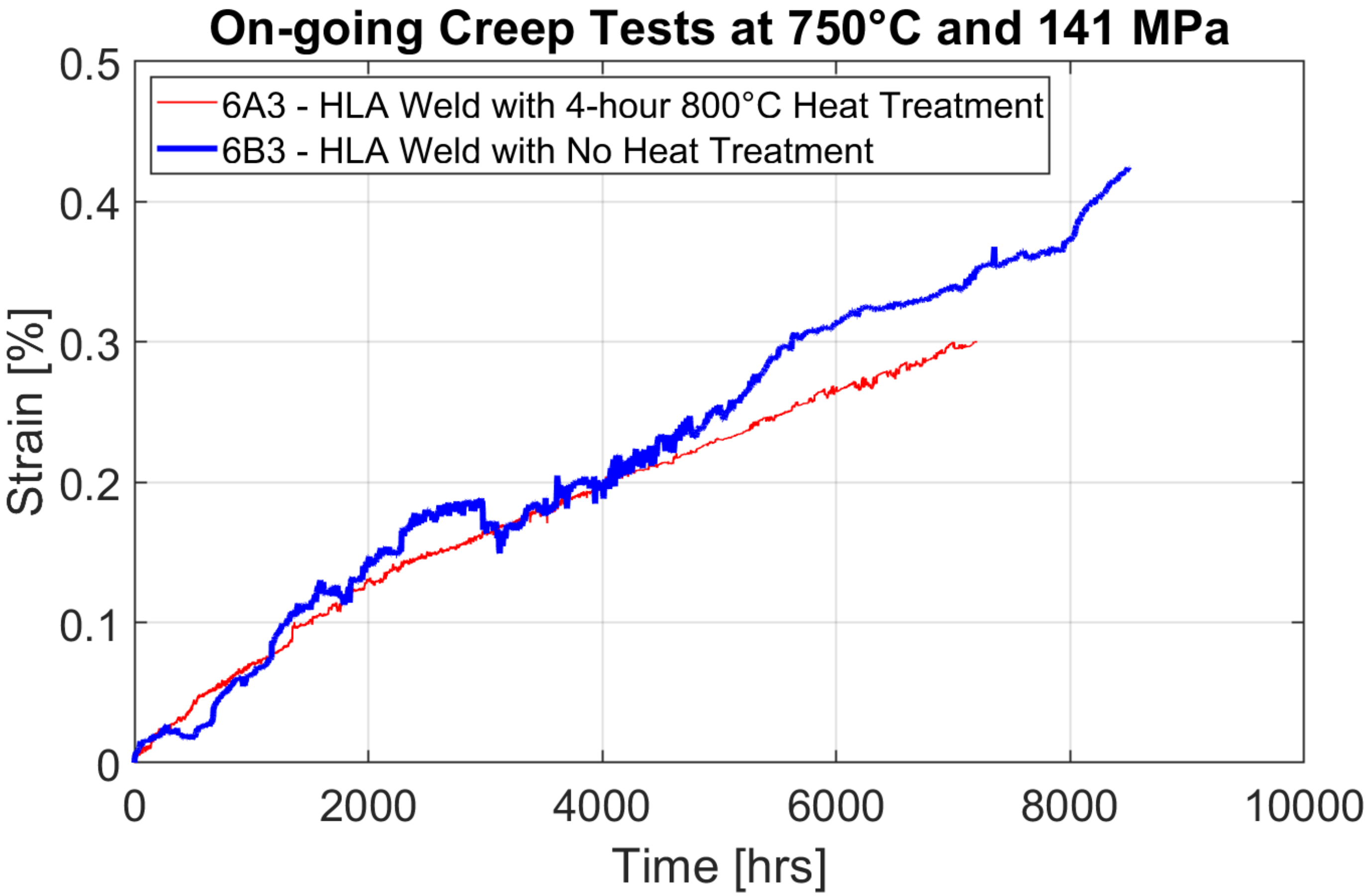


3 kW laser power

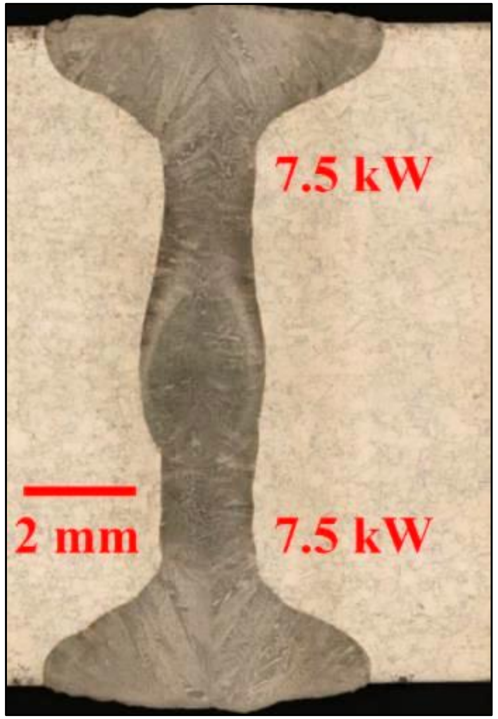


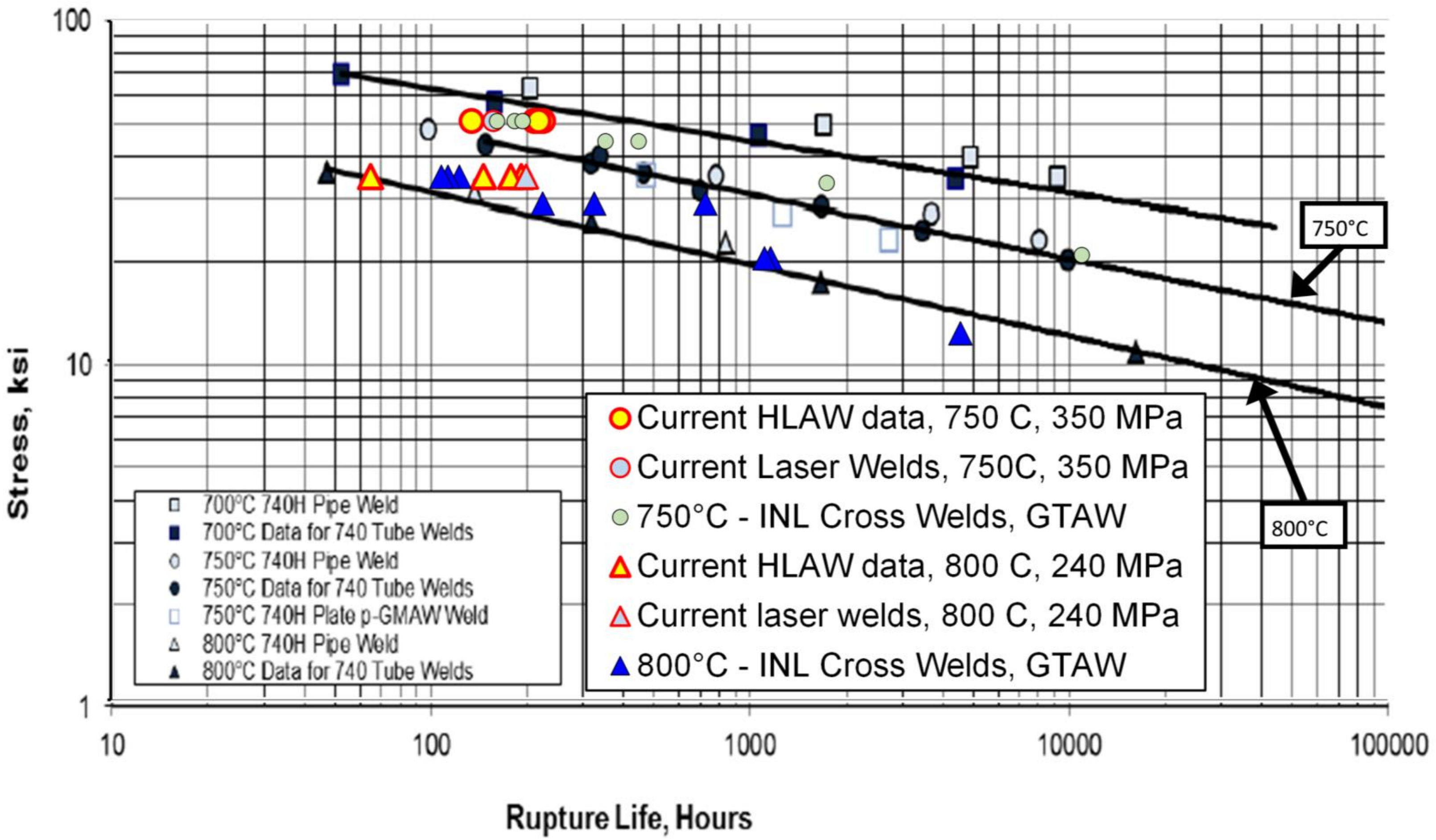
Long Term Creep Tests





Short Term Creep Tests





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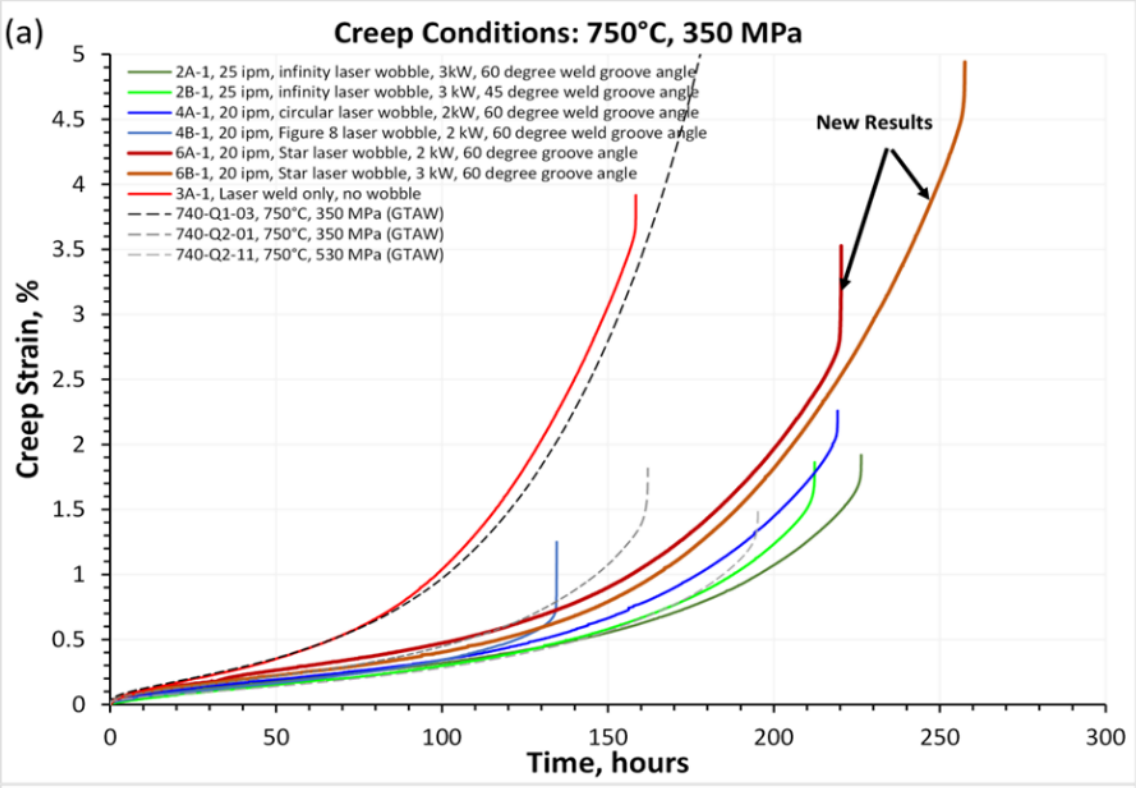
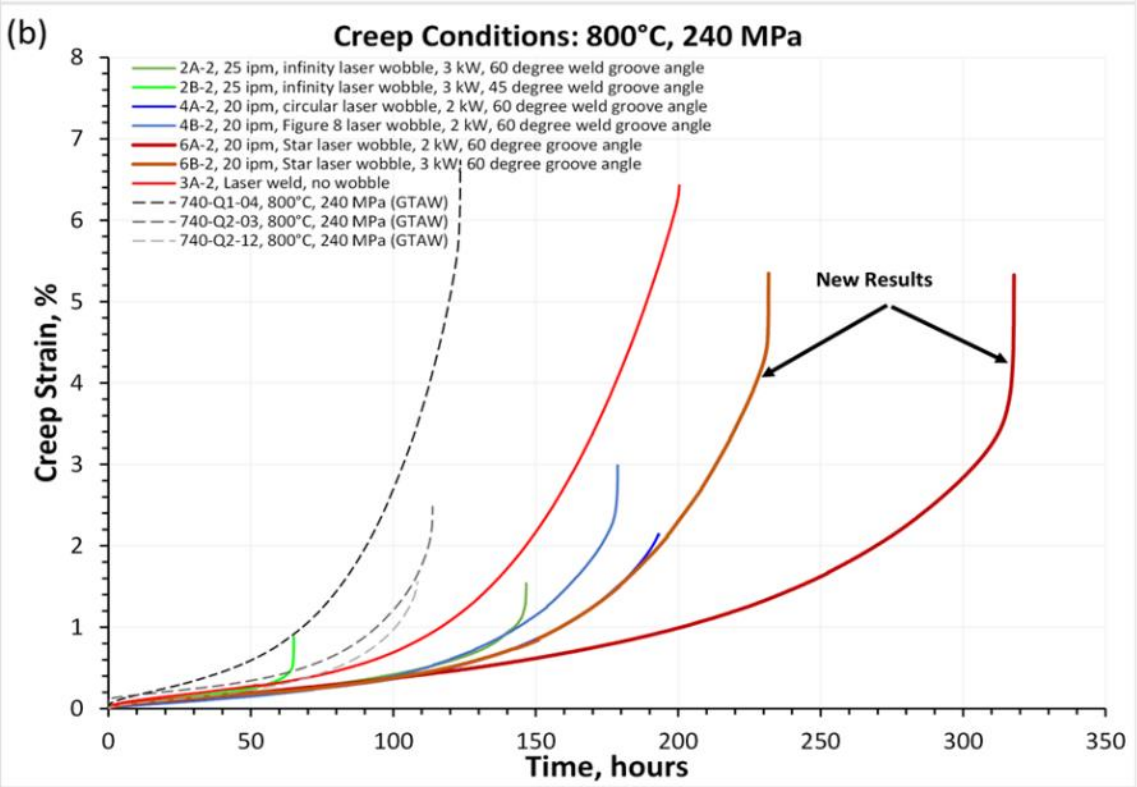
Short Term Creep Tests





Conclusions

Laser Welds

- Alloy 740H is highly susceptible to horizontal solidification cracks, keyhole collapse porosity, and heat affected zone liquation cracks

Laser Weld Modeling

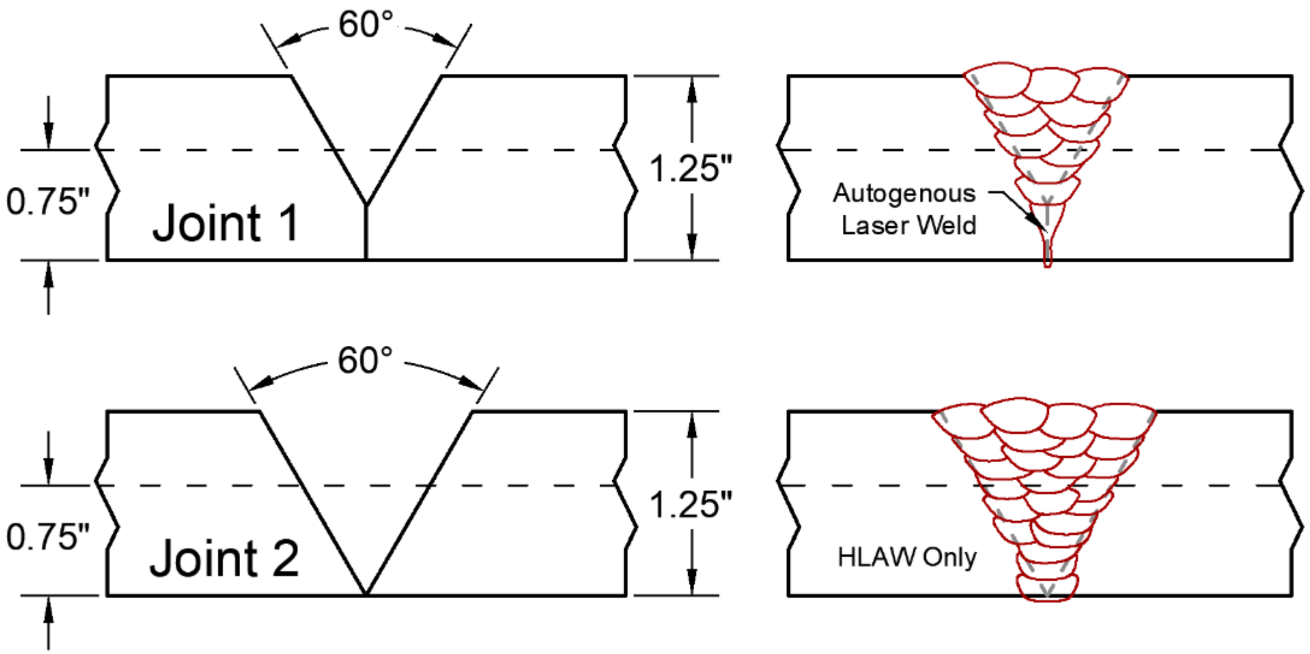
- Vertical stress state is highest across the mushy zone (liquid-to-solid transition) region where horizontal cracks occur

Laser and Hybrid Laser Arc Welding

- HLAW remain susceptible to solidification and liquation cracking
- Creep behavior of laser-only and hybrid welds remains equal to (or better) than conventional GTA welds

Future Work

- Complete defect free hybrid laser arc welds and productivity improvement demonstration
  - Complete two, 1.25” thick joints using a reduced travel speed and reduced wire feed speed to mitigate solidification cracking



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Modeling of Laser Wobble

- Cycloid beam propagation analysis

$$x = \frac{A}{2} cos \frac{2V_t}{A} t + V_f t$$

$$y = \frac{A}{2} sin \frac{2V_t}{A} t$$

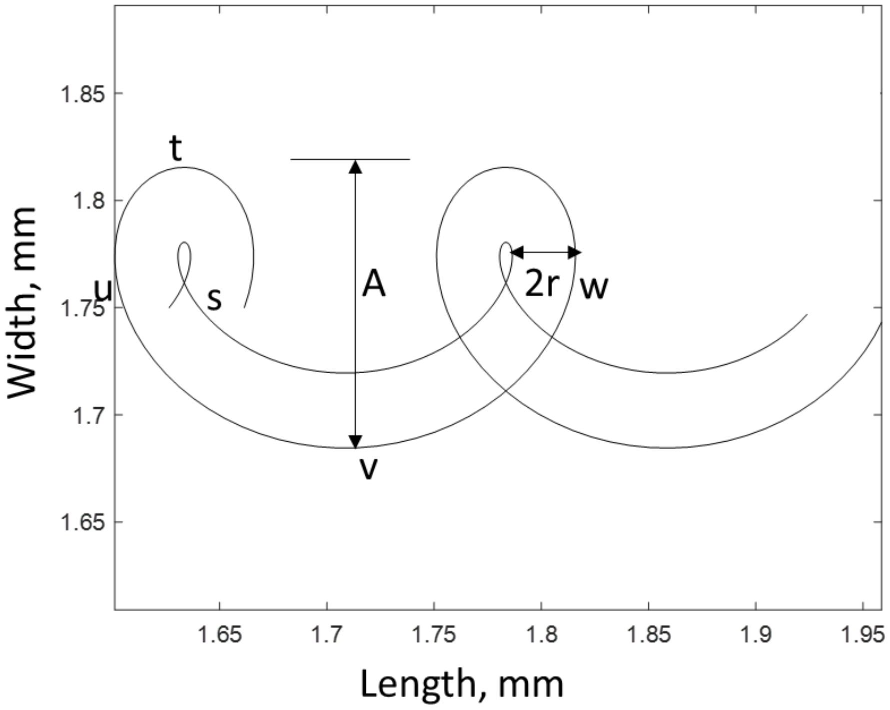
$Where$:

$A = amplitude$

$V_t = tangential\ velocity$

$V_f = angular\ velocity = f \cdot \pi \cdot A$

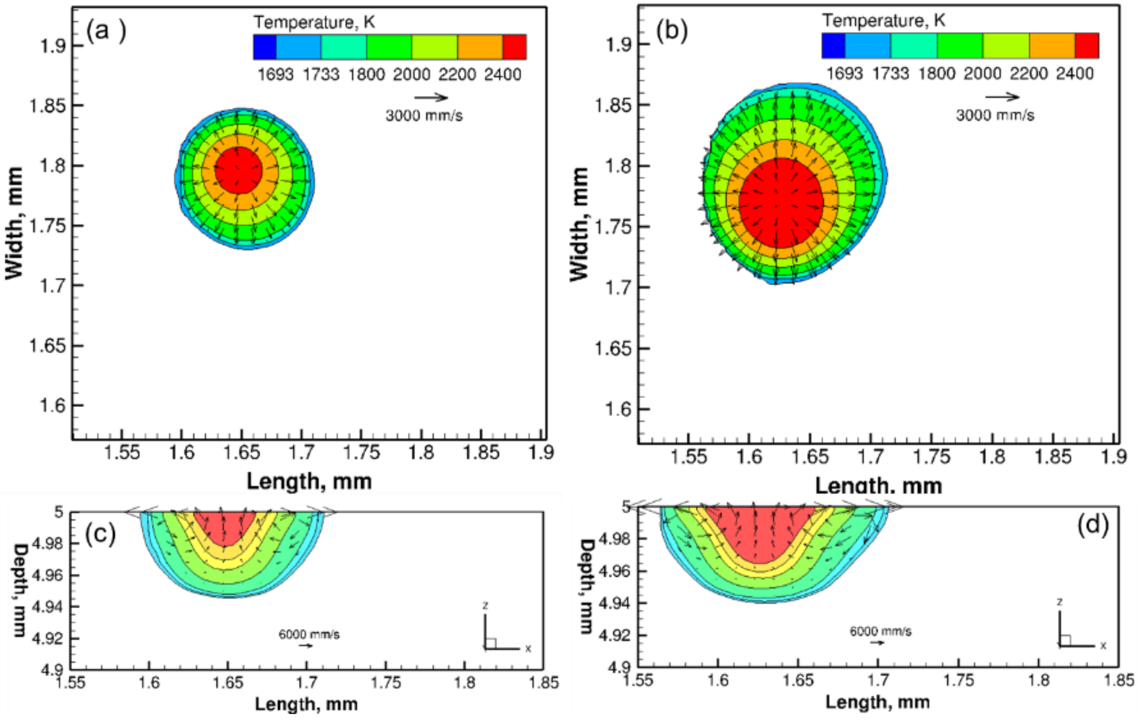
$f = frequency$

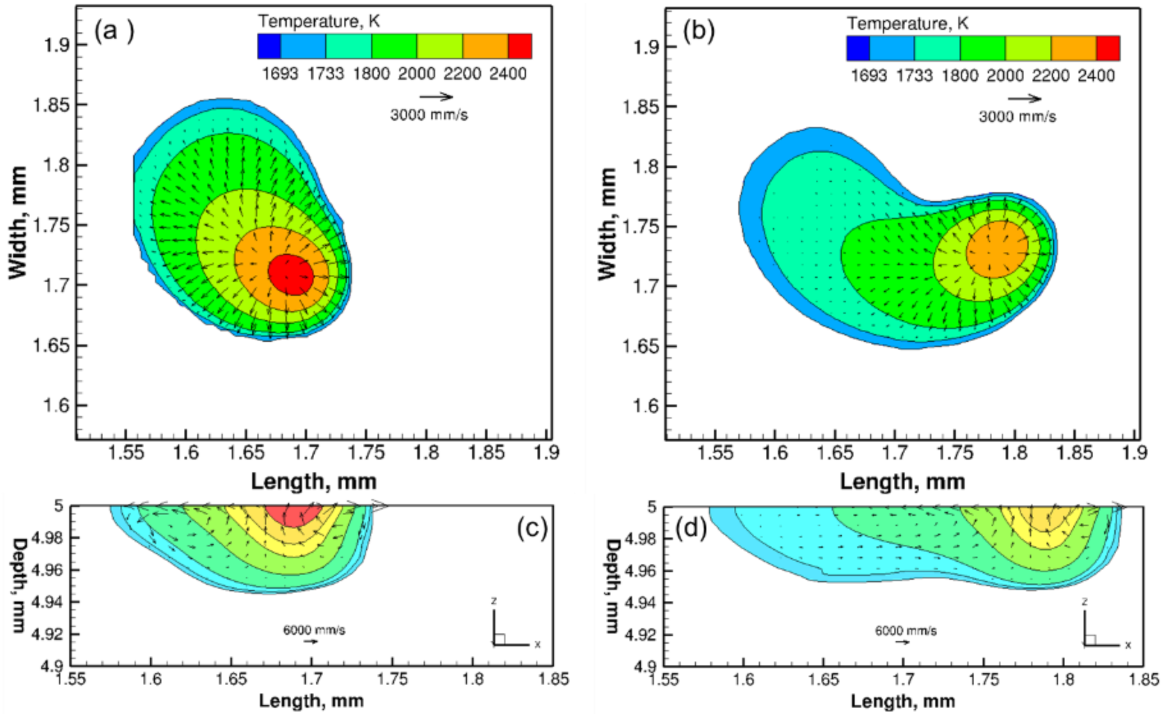


Parameters	
Laser power (W)	250
Welding speed (mm/s)	300
Laser radius (mm)	0.035
Amplitude (mm)	0.103
Frequency (Hz)	2000
Laser distribution	Gaussian

Modeling of Laser Wobble

- Cycloid beam propagation coupled to transient heat transfer and fluid flow that solves conservation of mass, momentum, and energy





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Modeling of Laser Wobble

- Peak temperature and cooling rate during laser wobble