INL/CON-22-66872-Revision-0

Multi-Pass Hybrid Laser Arc Welding of Alloy 740H

May 2022

Changing the World's Energy Future

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Idaho National Laboratory

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Multi-Pass Hybrid Laser Arc Welding of Alloy 740H

(FWP-B100-19010)

2021 Crosscutting Research and Advanced Energy Systems Project Review Meeting
Advanced Manufacturing

PennState

Idaho National Laboratory

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Background

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

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

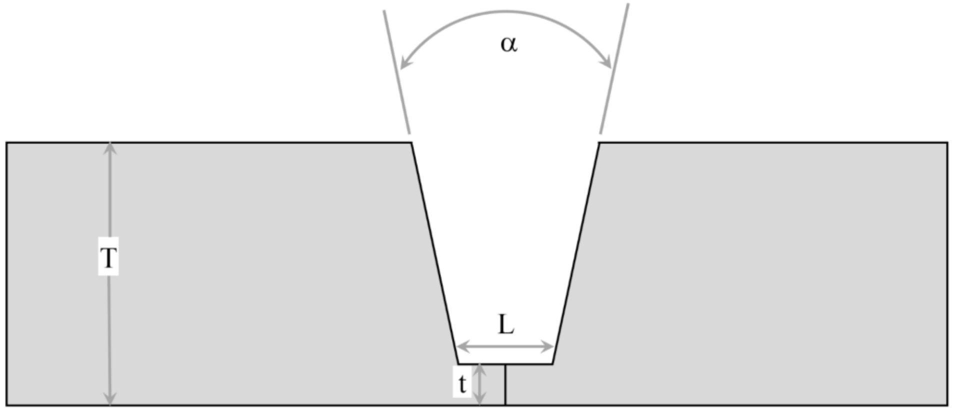
Approach

Objective:

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

Strategies

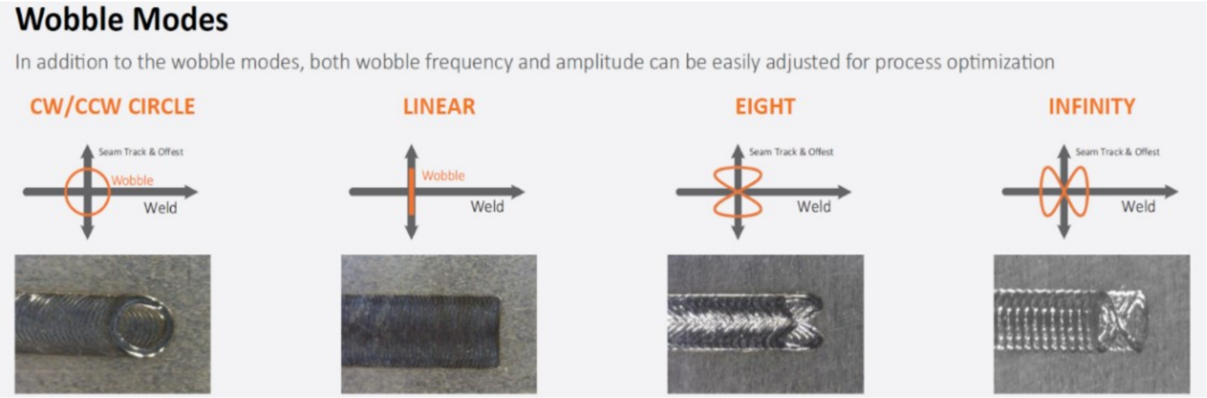
- Deep Penetration laser welding of thick weld groove lands (t~12.7 mm)
- Increase speed/deposition rate of weld groove filling using Hybrid Laser Arc Welding (HLAW)
- Incorporate laser wobble to decrease defects, improve microstructure and improve weld strength reduction factor (WSRF)
- Narrow weld groove design, α – reduce weld volume

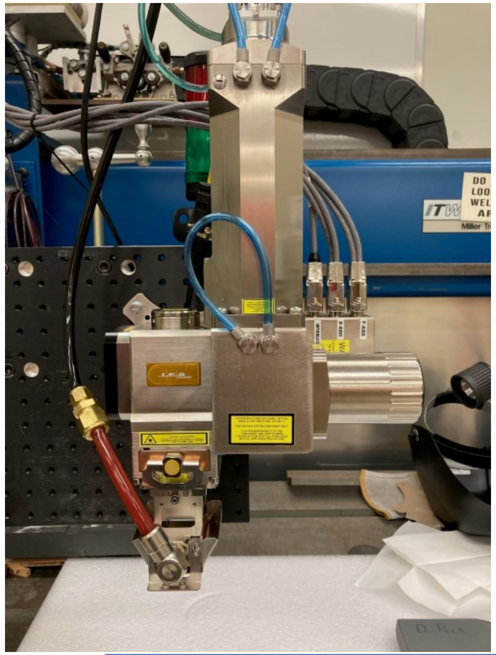


Weld Groove Design

Laser Wobble

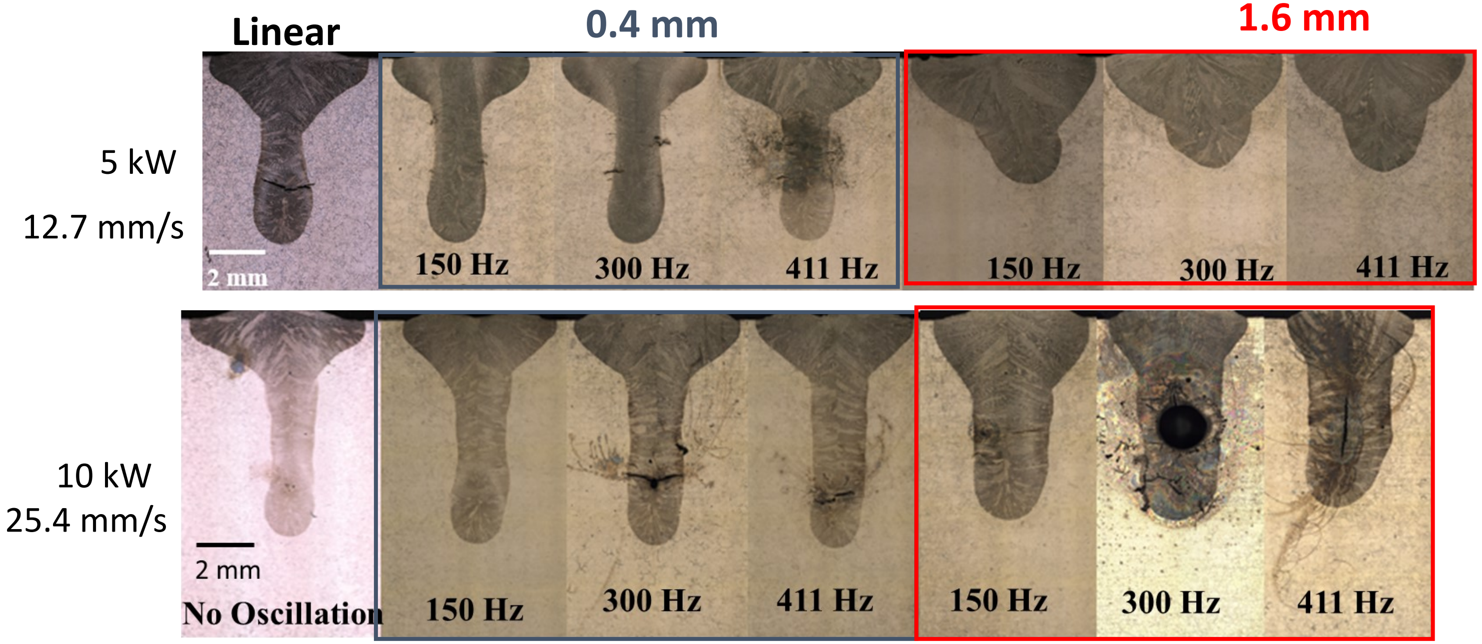
- PSU - Laser weld 12.7 mm thick weld groove land (10 kW laser, 30 ipm)
- INL - Hybrid Laser Arc Welding (HLAW) for weld groove filling (3kW laser, 20-40 ipm)
- Laser wobble for defect reduction at increased travel speed:

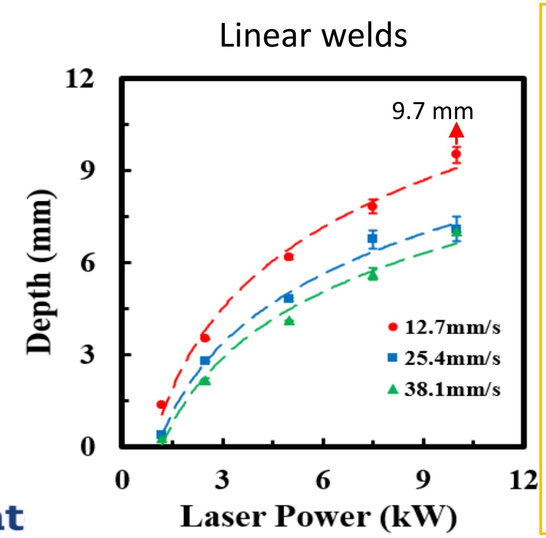


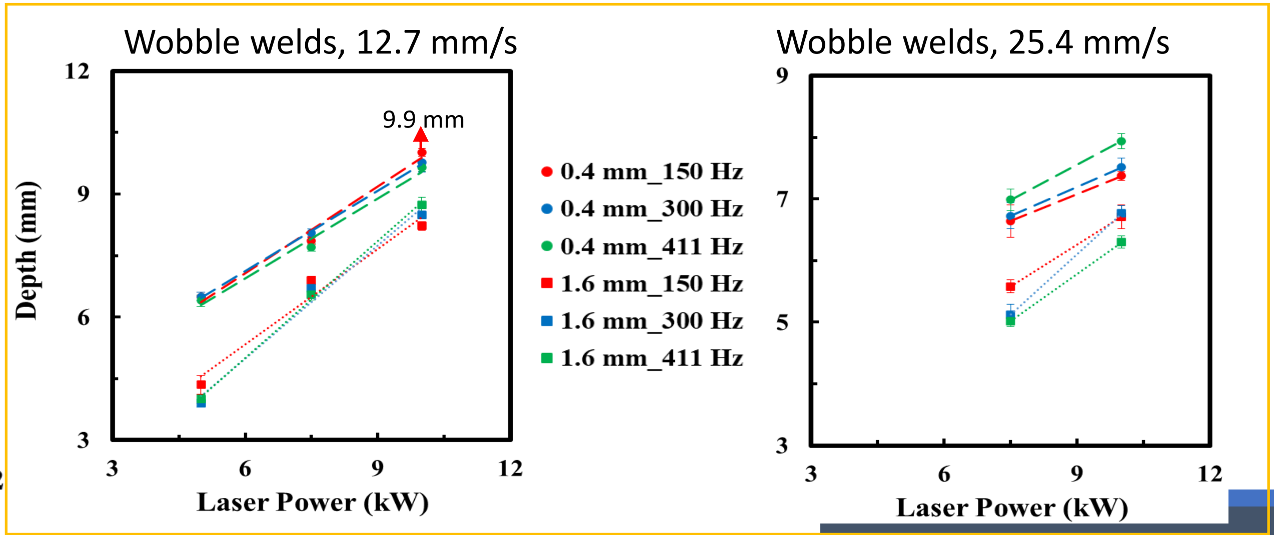


Deep Penetration Land Welding Development with Modeling and Simulation

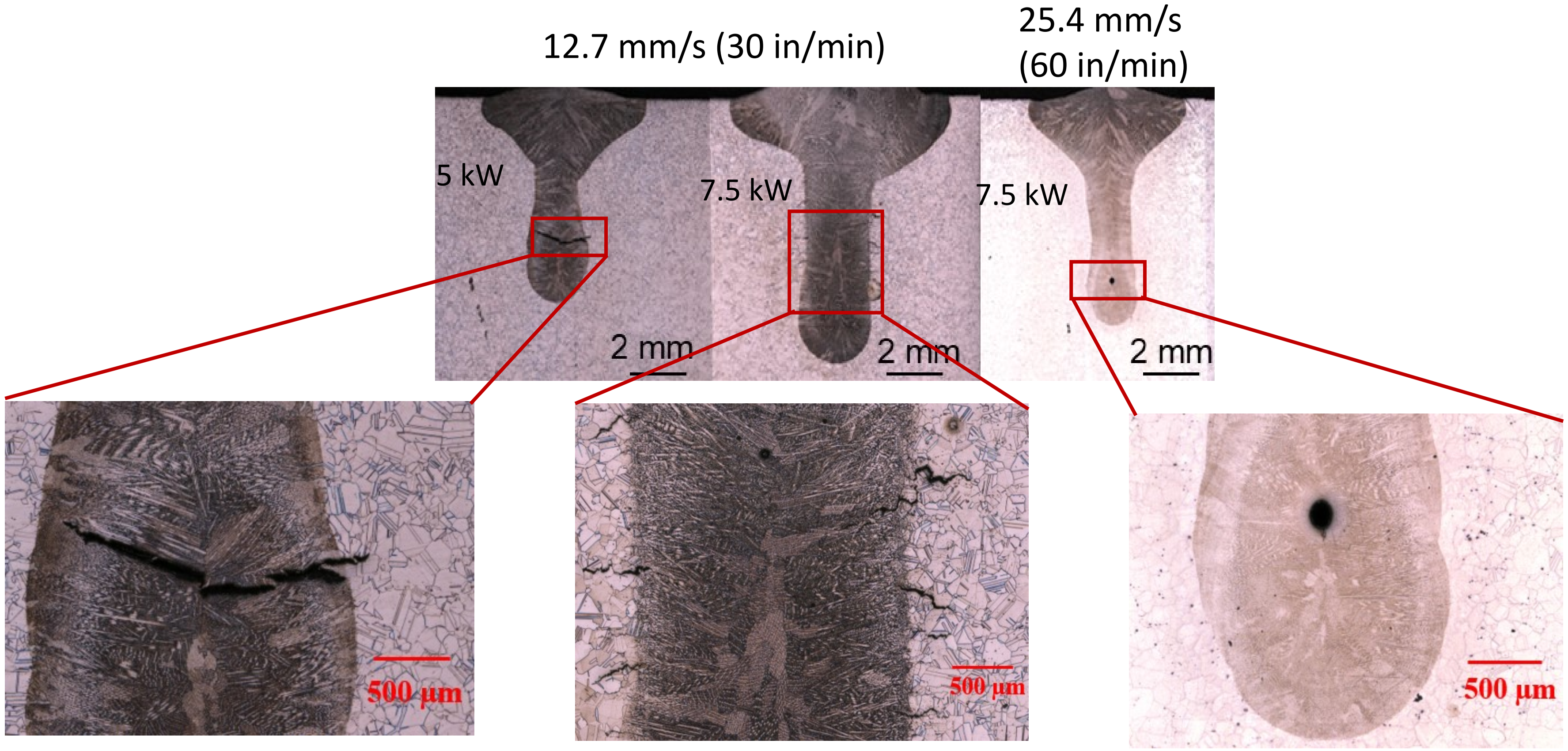
Comparison of Linear and Wobble Weld Dimensions







Defects in Linear Laser Keyhole Welding of IN 740H

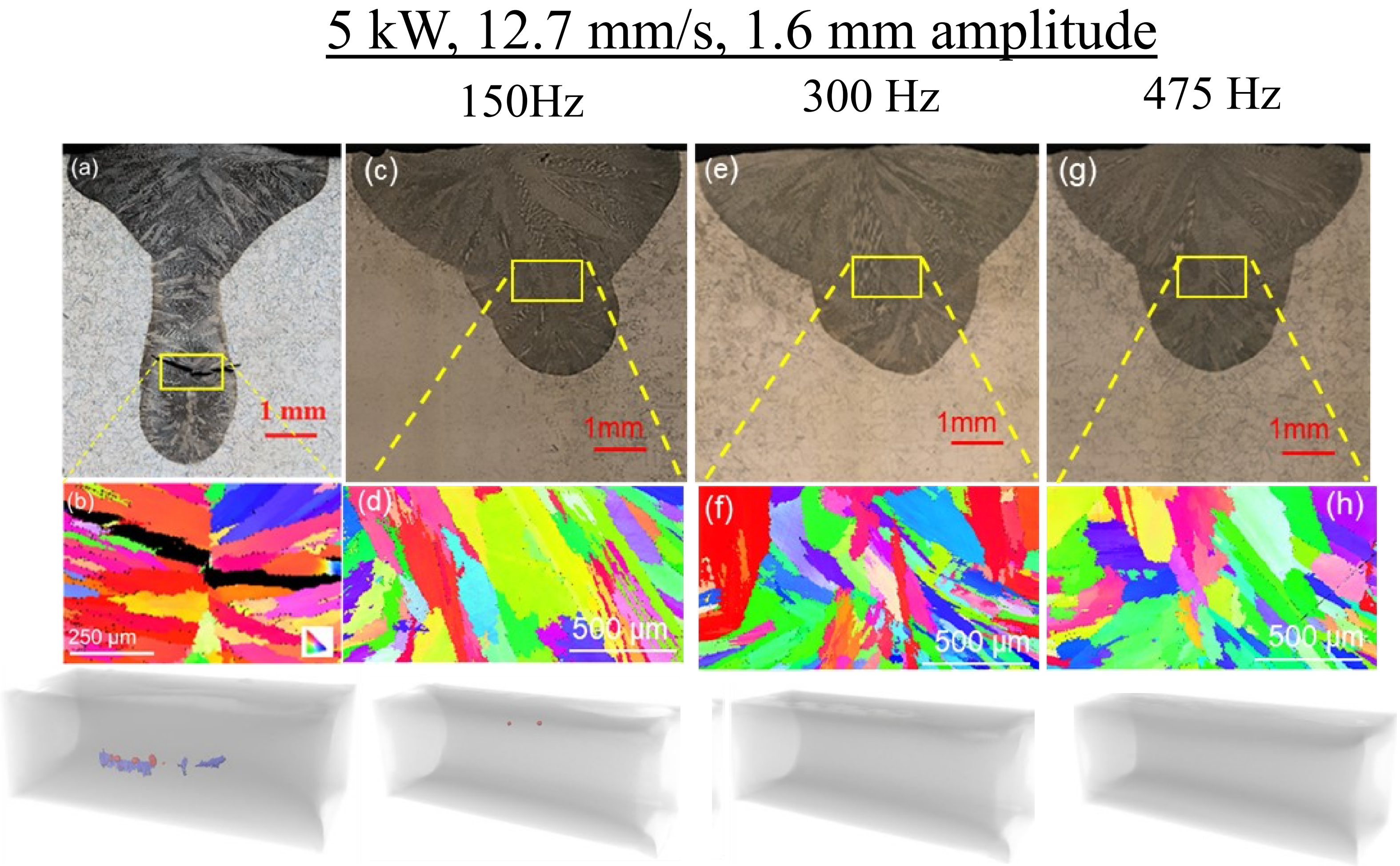


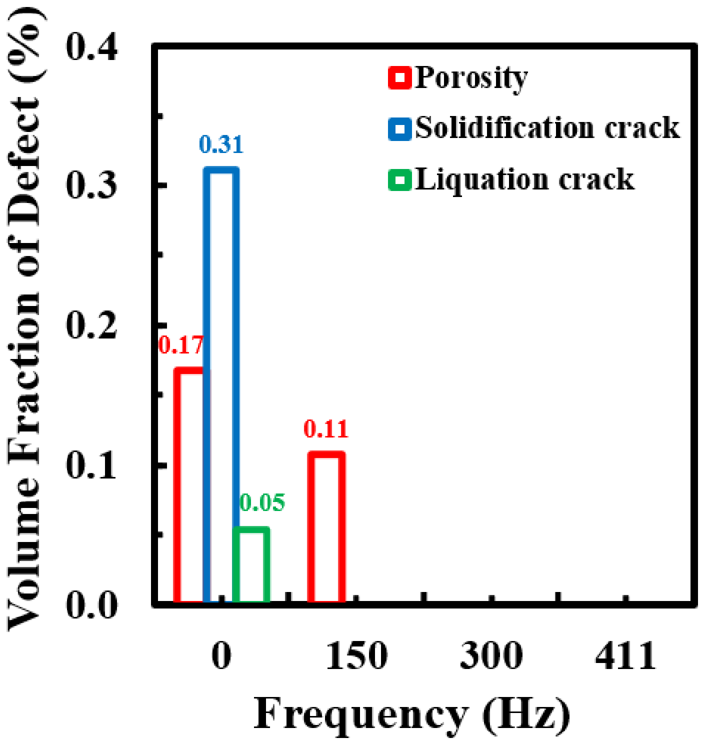
Intergranular solidification cracks observed along weld centerline in fusion zone

Multiple liquation cracks observed in the HAZ

Keyhole collapse porosity present in higher speed welds

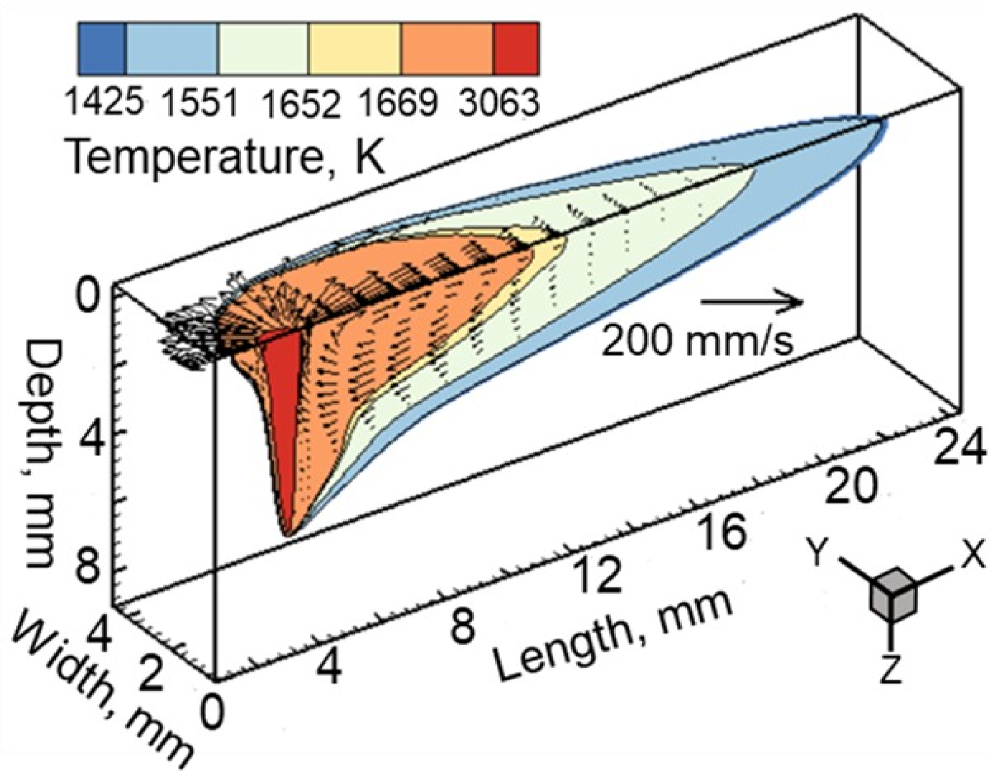
Change from Oriented Grains in Linear Welds to Random Grain Structure in Wobble Welds





Modeling of Wobble Welding

Heat Transfer and Fluid Flow Model of Laser Keyhole Welding



5kW, 12.7 mm/s (30 in/min)

A well-tested numerical heat transfer and fluid flow model can calculate the vulnerable and relaxation times.

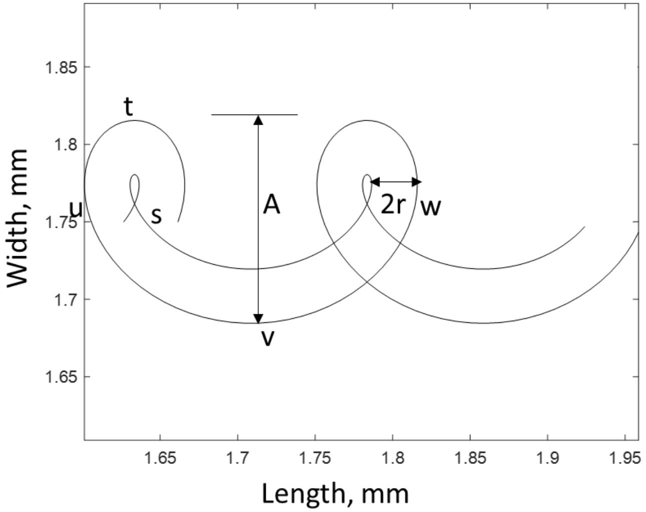
Solves Navier Stokes and Energy equations numerically.

Model input: alloy thermophysical properties and laser welding variables.

Model output: temperature and velocity distributions in 3D, temperature gradients, cooling rates, solidification parameters, solid fractions in the two-phase region.

The ratio of vulnerable time to relaxation time ratio is calculated at different elevations of the weld.

Modeling Laser Wobble Welding

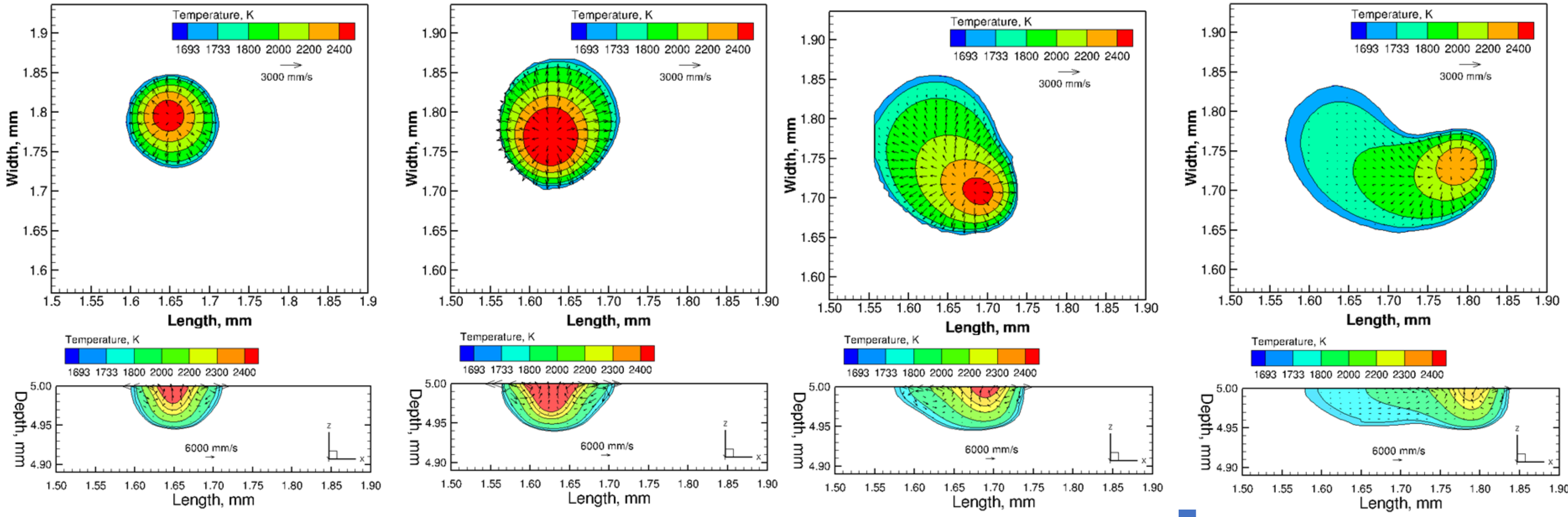


$$x = \frac{A}{2} cos \frac{2V_t}{A} t + V_f t$$

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

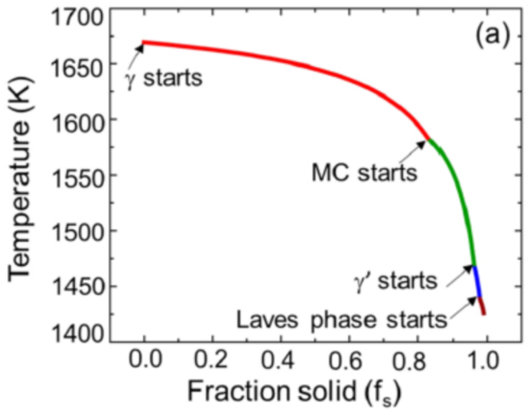
$$V_t = f * \pi * A$$

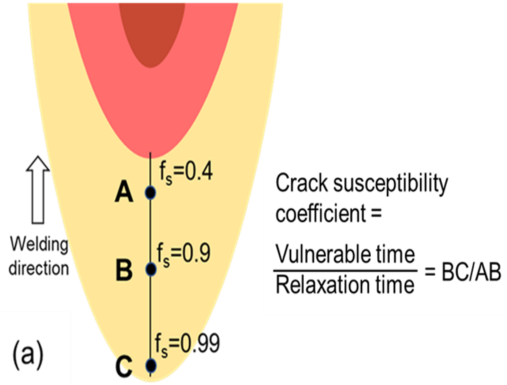
Parameters	Values
Laser power	250 W
Welding speed (vf)	30 cm/s
Laser radius	0.0035 cm
Amplitude (A)	0.0103 cm
Frequency (f)	2000 Hz
Laser distribution	1

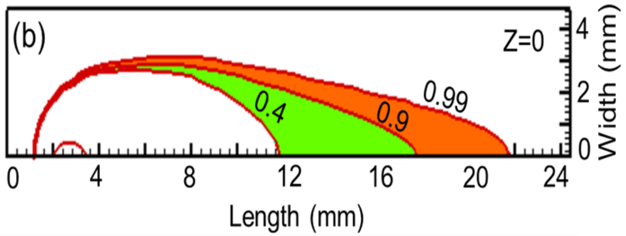


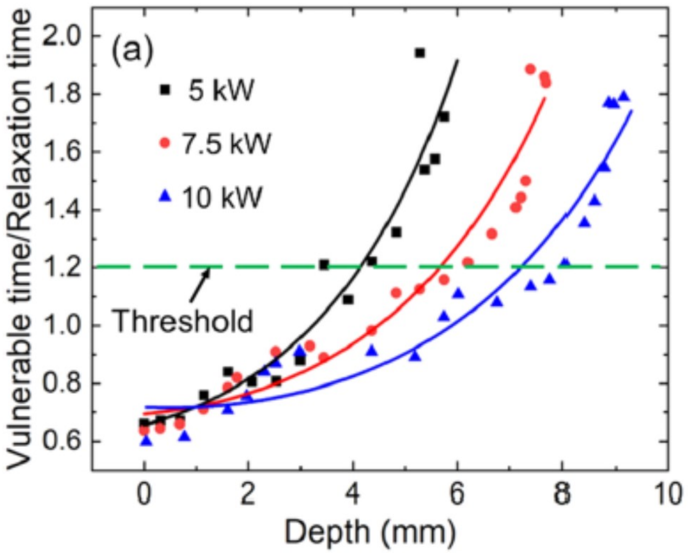
Appearance of Solidification Cracking at High Laser Powers

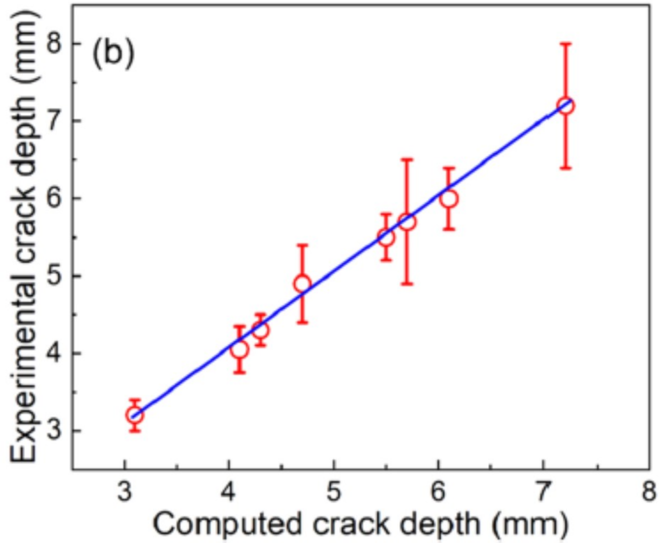
Cracking Susceptibility Coefficient in Linear Welds





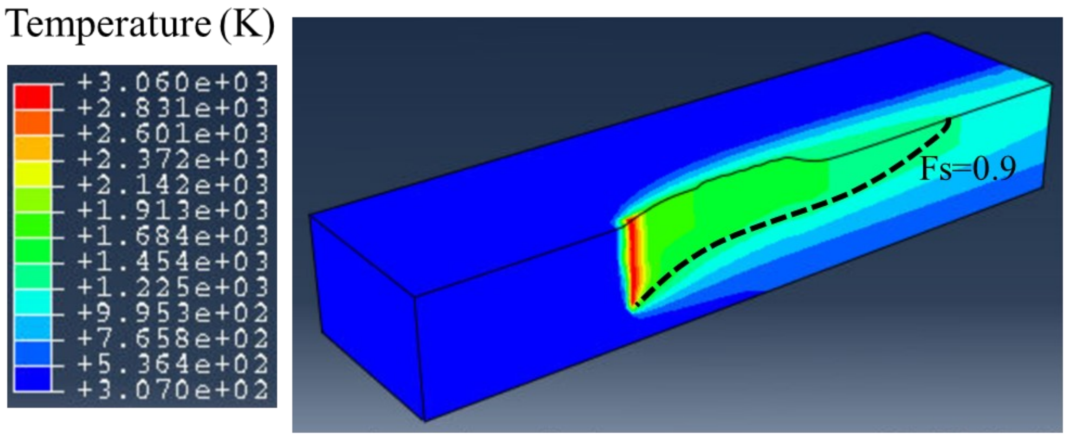


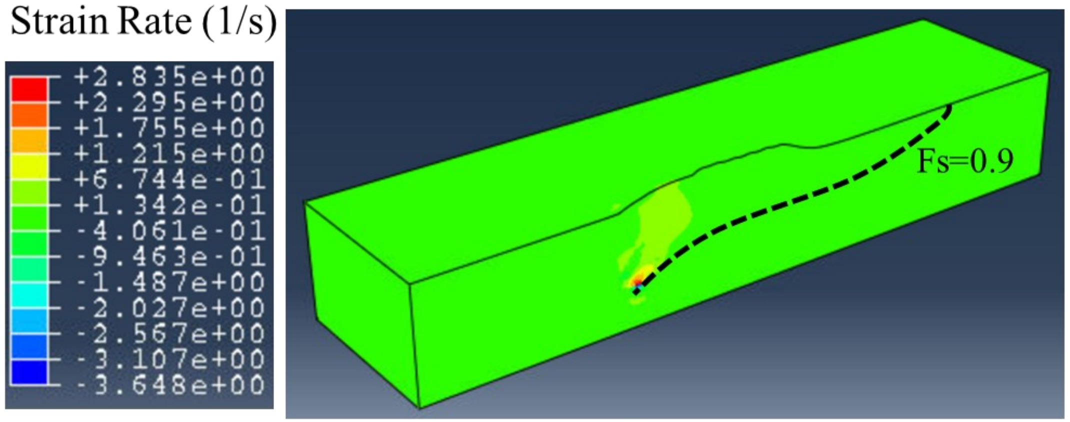


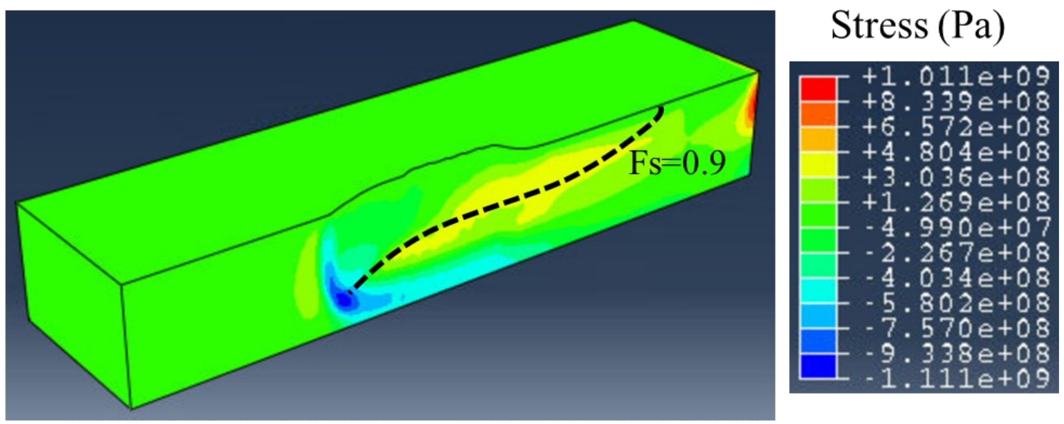


Clyne and Davis, 1981, British Foundryman

Vertical Stress State Along Central Longitudinal Plane at a Fraction of Solid (Fs) of 0.9







Horizontal crack will likely occur where a critical strain rate is attained while vertical stress is in tension

Weld Groove Filling by HLAW

Main Objectives:

- Increase travel speed and filler wire feed speed
- Minimize weld groove area

Table of Hybrid Conditions:

ID	Laser Power	Wobble Pattern	Frequency	Travel speed	Deposition rate	Heat Input
2A	3 kW	Infinity	85 Hz	25 ipm	8.1 lb/hr	27.9 kJ/in
2B	3	Infinity	85	25	8.1	27.9
4A	2	Circular	170	20	7.6	30.4
4B	2	Fig. 8	85	20	7.6	30.4
6A	2	Star	51	20	7.6	30.4
6B	3	Star	51	20	7.6	33.4

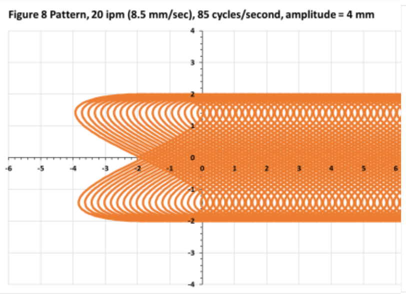
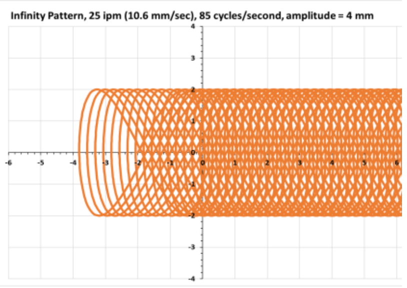
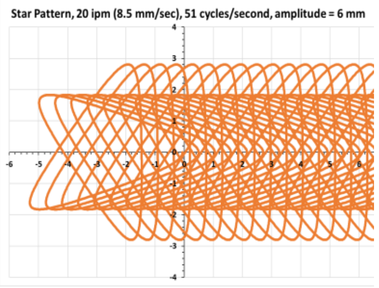


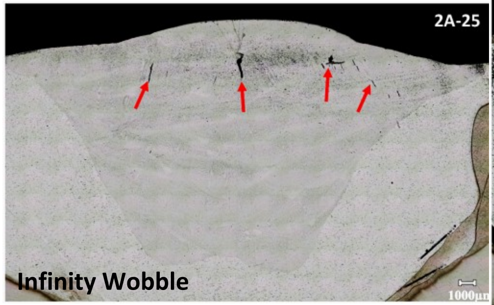
Figure 8 Wobble

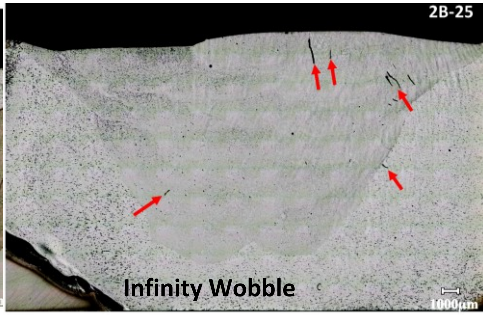


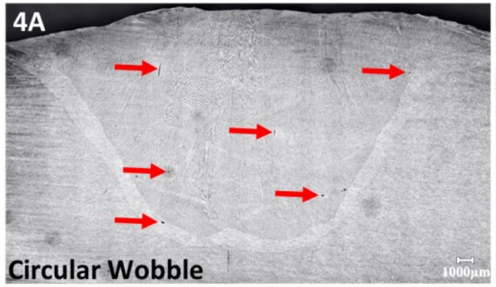
Infinity Wobble

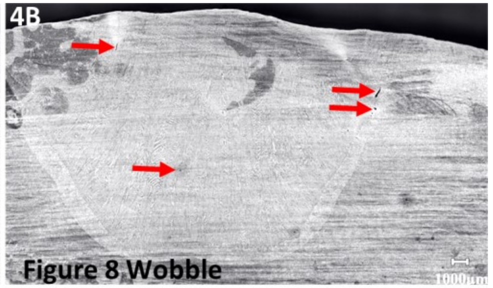


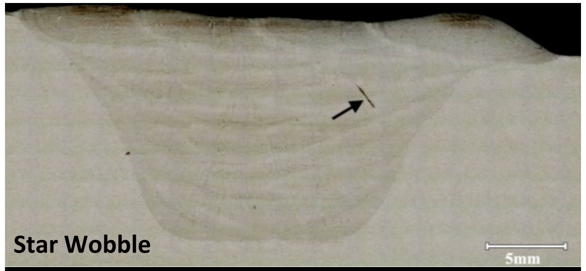
Star Wobble

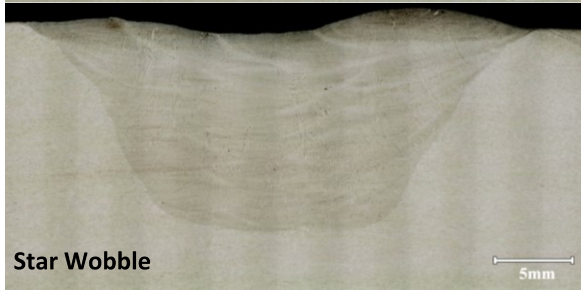




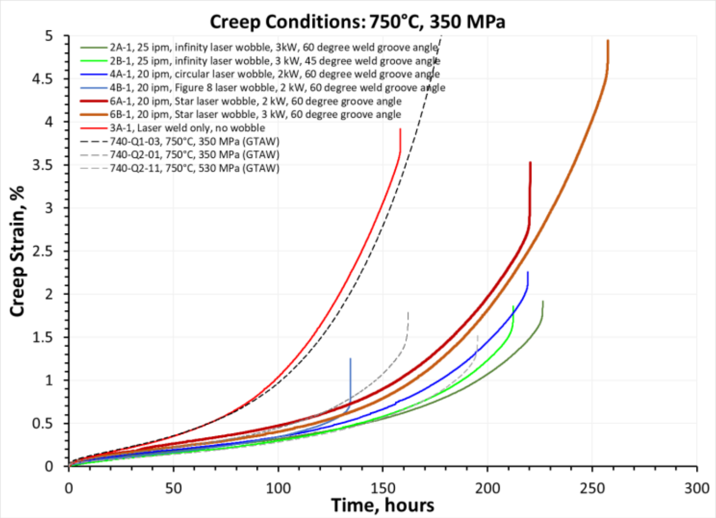


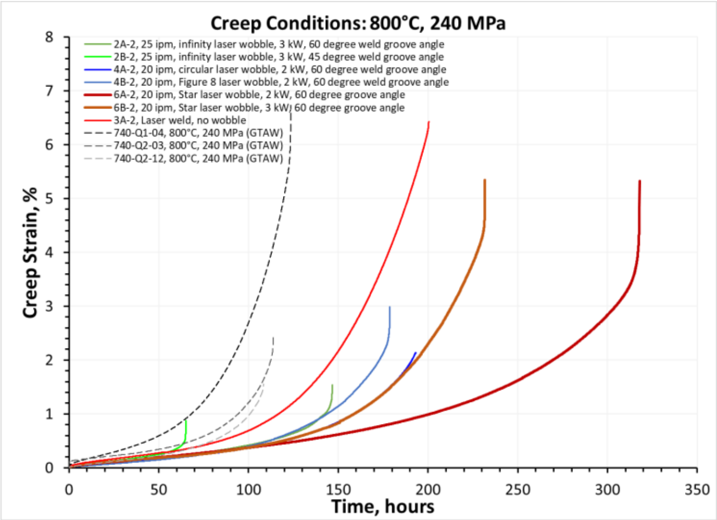


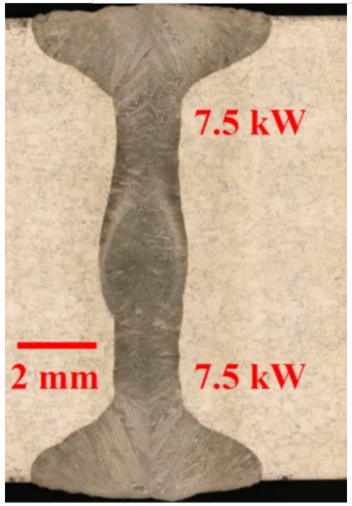




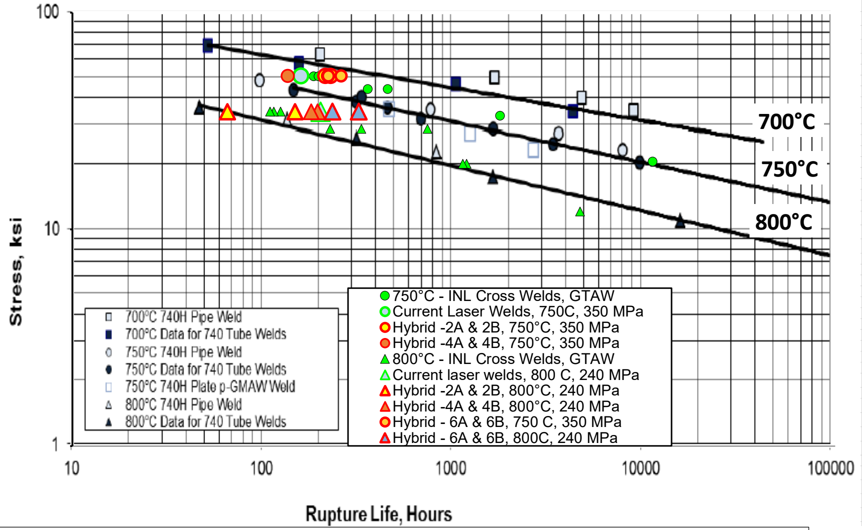
Short-term, Cross-weld Creep Behavior





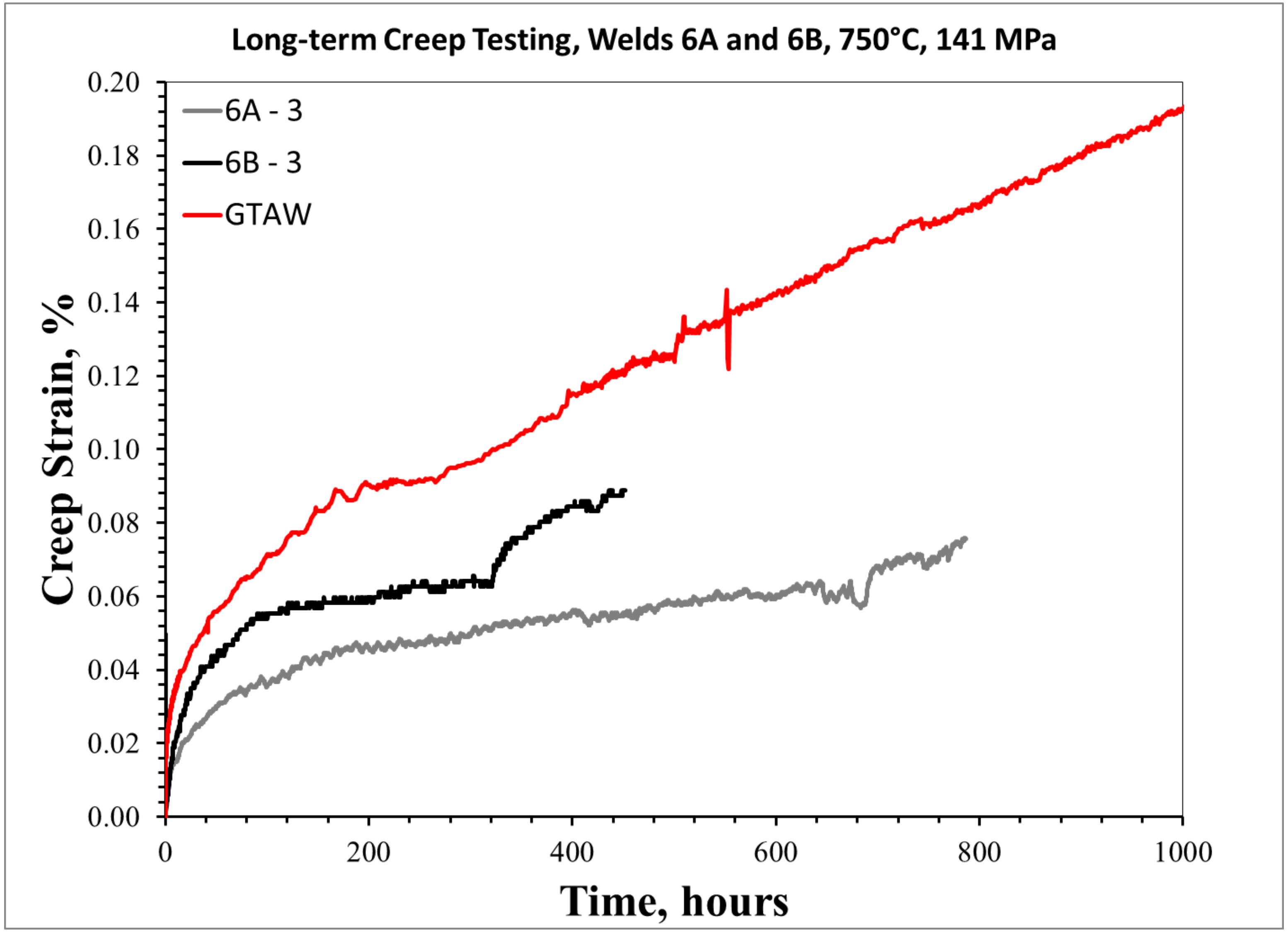


Laser weld width ~2 mm vs ~25 mm for Hybrid weld



Conclusion: Laser & hybrid welds equivalent to GTA welds

Long-term, Cross-weld Creep Tests



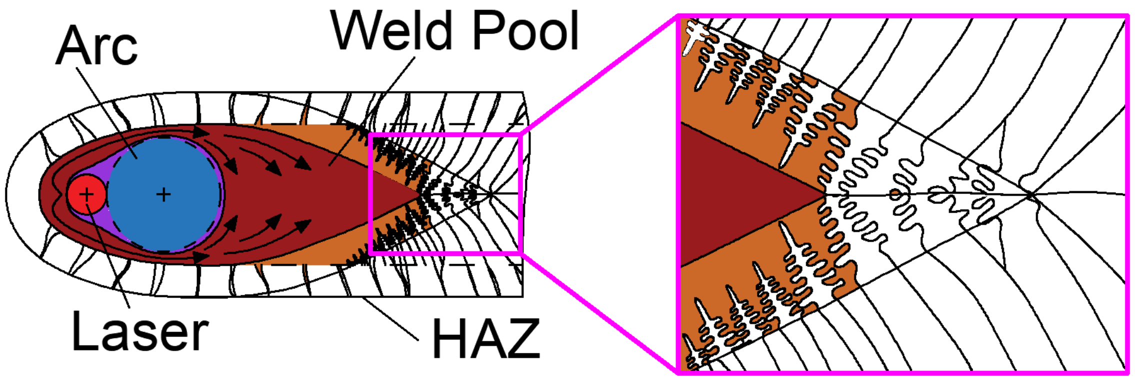
Near Term Experimental Studies

Laser Location Effects:

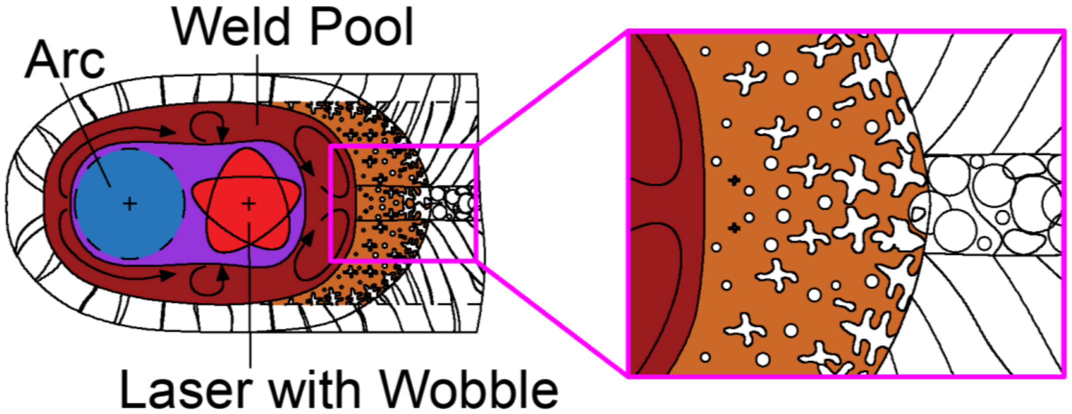
- Laser-leading setup
  - Arc stabilization
  - Acts as additional heat source

- Laser-trailing setup
  - Arc stabilization
  - Acts as additional heat source
  - ***Affects solidification microstructure***

Laser-leading



Laser-trailing

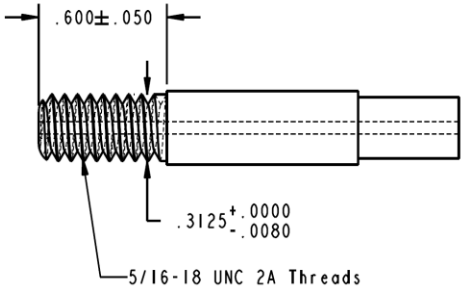


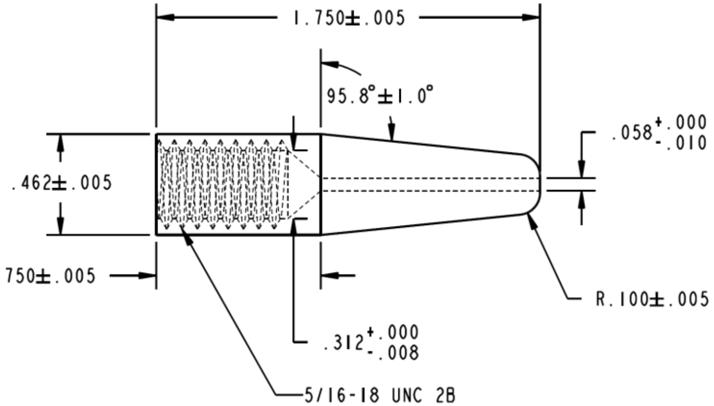
Near Term Experimental Studies

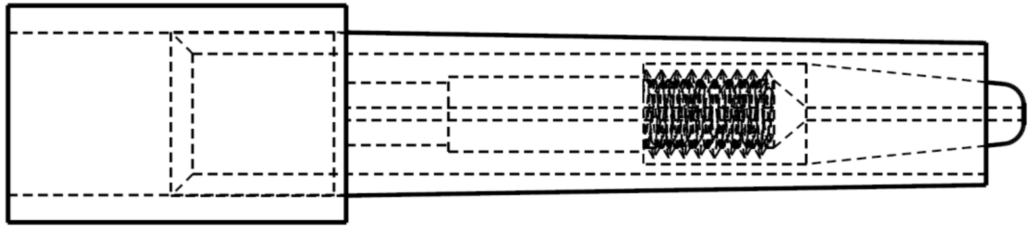
<u>Narrow Groove Trials</u>

- Narrow groove joint design
  - Reduces total weld volume and welding time

- Modification of GMAW torch
  - Thick welds
  - Compatible with:
    - Laser-leading
    - Laser-following



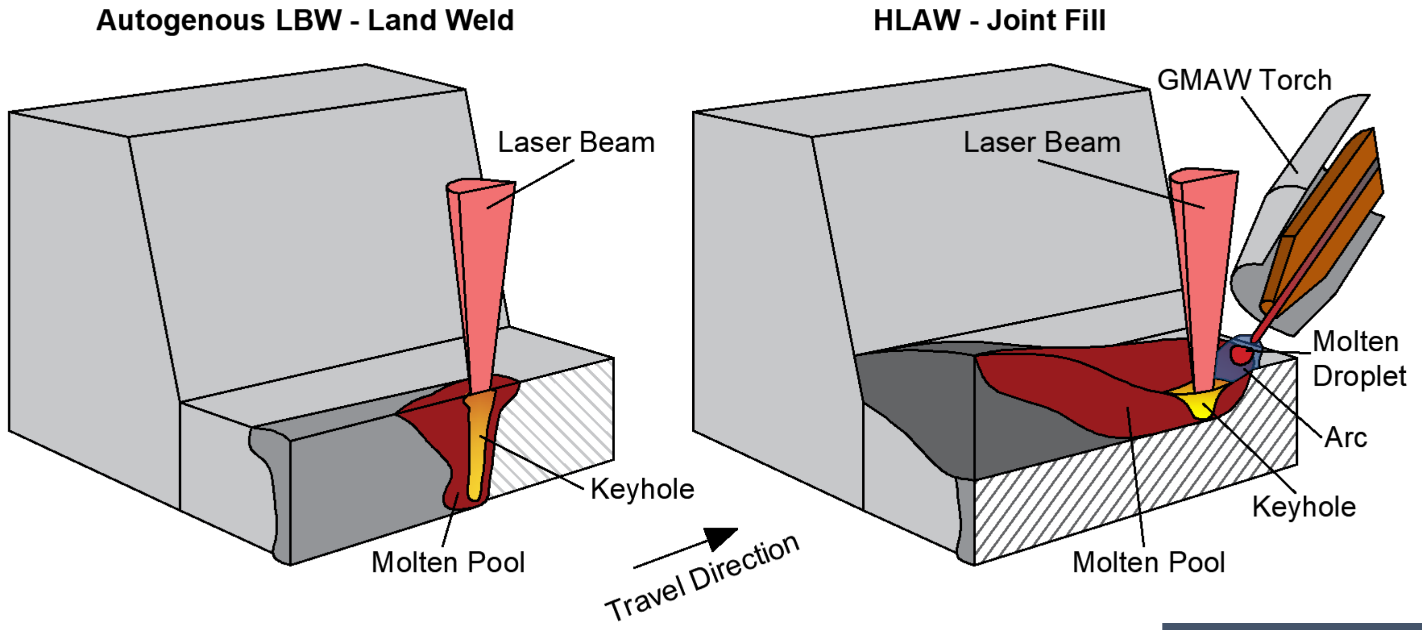




Near Term Experimental Studies

Combined Laser/HLAW Welds in Thick Plate

- Full welds
  - Deep penetration weld groove land welds
  - Hybrid laser arc weld groove filling (narrow groove)
- 32 mm thick plate welds
- 76 mm thick plate welds



Summary and Conclusions

- Deep penetration laser welding of thick weld groove lands
  - Laser wobble capable of reducing defects vs. linear laser welds
  - Modeling and simulation
    - Began modeling of laser welding with laser wobble
    - Explored cracking issues associated with linear laser welds
- Laser-only and hybrid conditions have been identified that yield sound welds at TS > ~2x
- Short-term creep behavior of laser-only and hybrid welds is equal to (or better) than conventional GTA welds
- Long-term creep testing was initiated
- Path forward focused on complete welds in thick plate and documenting productivity improvements

Manuscripts:

- B. Mondal, M. Gao, *T. A. Palmer*, and T. DebRoy, “Solidification Cracking of a Nickel Alloy during High Power Keyhole Mode Laser Welding”, in press, *Journal of Materials Processing Technology*, 305 (2022), 117576.
- T. Lillo, T. Patterson, T. Palmer, “Characterization of Laser Welds and Hybrid Laser Arc Welds in Alloy 740H”, in development.

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