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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
- 100,000 hrs at 760°C, 100 MPa
- 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

- Joining of thick sections:
  - Gas Tungsten Arc Welding – best properties, slow
  - Gas Metal Arc Welding – fastest method, Weld Strength Reduction (WSRF) factor: 0.70
  - Submerged Arc Welding (SAW) – no flux has been developed

Approach

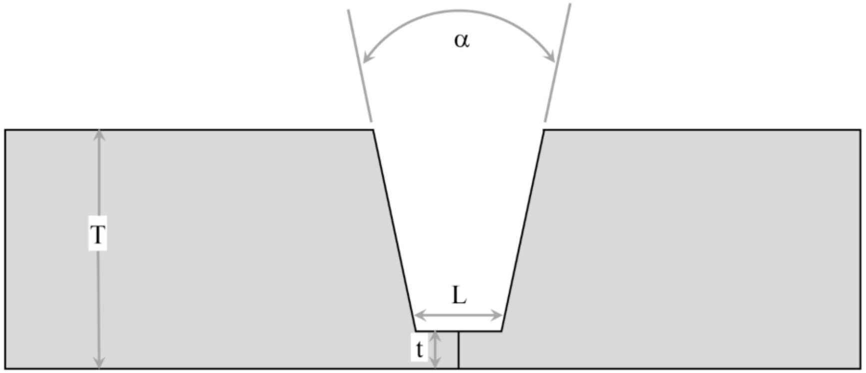
Objective:

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

- Strategies
  - Task 1: Deep Penetration laser welding of thick weld groove lands (~12.7 mm)
    - Laser welding of thick weld groove land
    - Modeling & simulation of laser welding Alloy 740H
  - Task 2: Productivity gains during weld groove filling by Hybrid Laser Arc Welding (HLAW)
    - HLAW parameters for weld groove filling
    - Minimization of weld groove area

Groove Area Reduction

Weld Groove Configuration



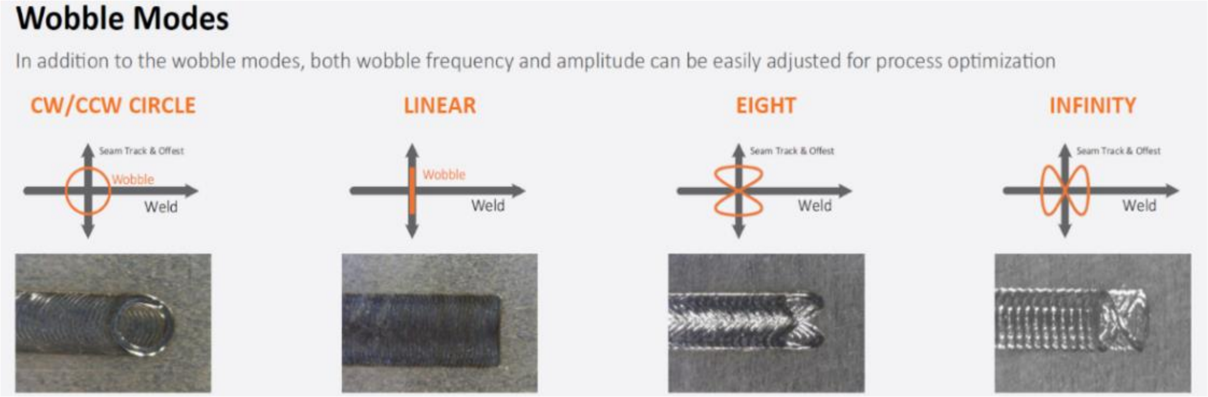
Weld Groove Configuration	t, in.	T, in.	L, in.	ϴ, degrees	Fill Area, in^2	Δ, %
Standard GMAW	0.125	3.0	0.5	60	6.2	-
Thick Land, t	0.5	3.0	0.5	60	4.9	-21.8
Narrow Land, L	0.5	3.0	0.125	60	3.9	-36.9
Reduced groove angle, ϴ	0.5	3.0	0.125	30	2.9	**-53.3**

Targeted changes:

- Primary – Increase weld groove land thickness (1/8” to 1/2”)
- Secondary –
  - Weld groove land width (reduce from 1/2” to 1/8”)
  - Included angle (reduce from 60° to 45°)

Increased Welding Speed

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



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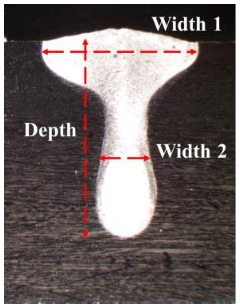
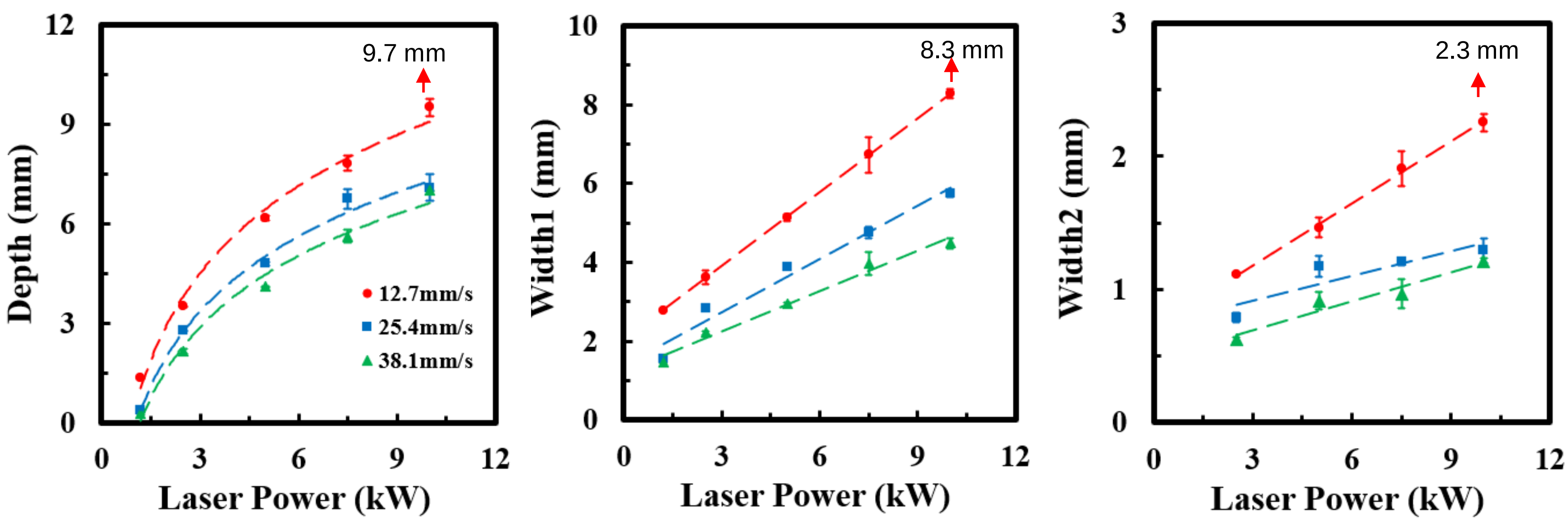
Task 1.B Deep Penetration Land Welding Development

Increasing Laser Power and Decreasing Travel Speed Leads to Increased Weld Depths



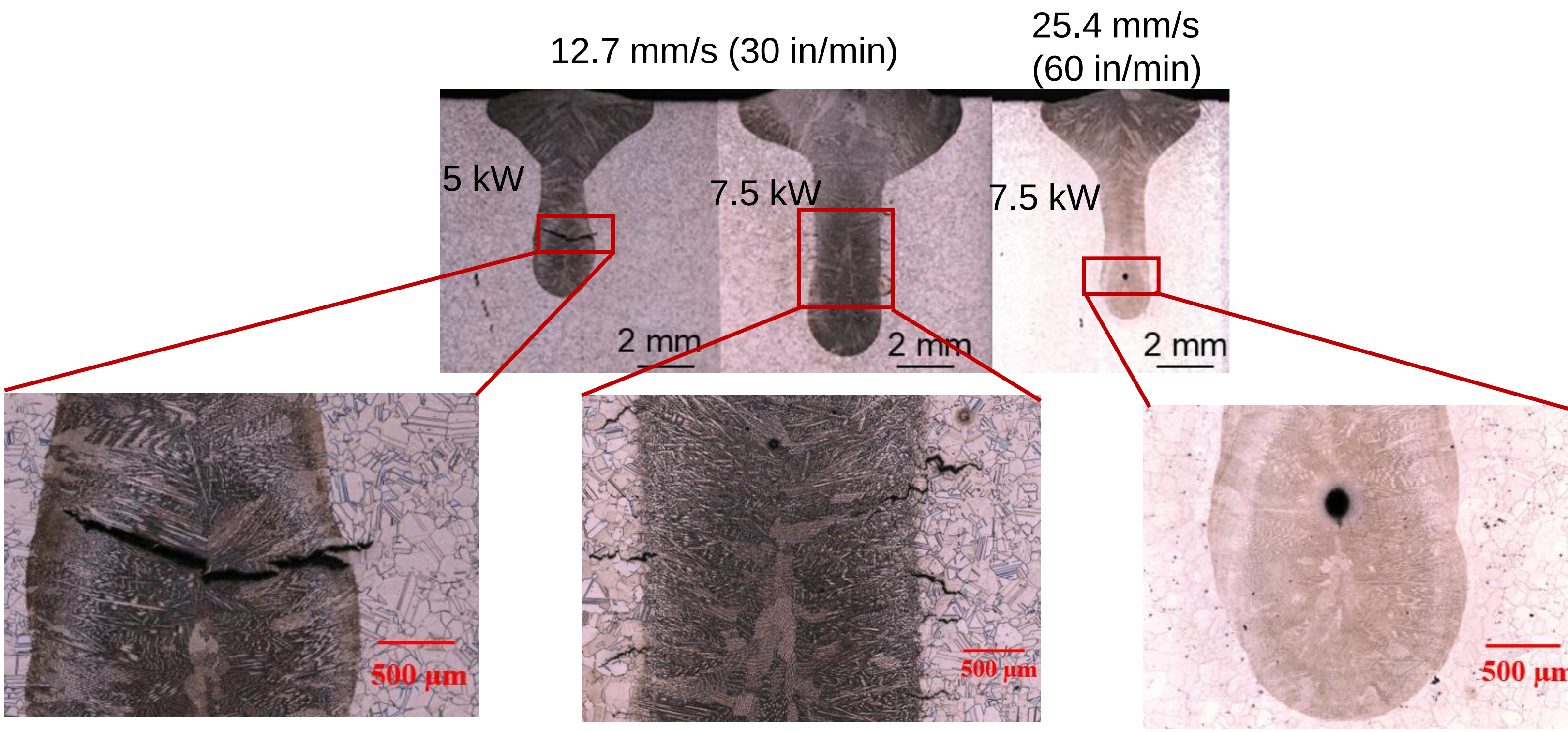
Speed (mm/s) / Power (W)	Depth (mm)			Width 1 (mm)			Width 2 (mm)		
	12.7	25.4	38.1	12.7	25.4	38.1	12.7	25.4	38.1
1200	1.3 ± 0.1	0.4 ± 0.1	0.3 ± 0.1	2.8 ± 0.1	1.6 ± 0.1	1.5 ± 0.1	0.6 ± 0.2	--	--
2500	3.5 ± 0.1	2.8 ± 0.1	2.3 ± 0.1	3.8 ± 0.2	2.8 ± 0.1	2.2 ± 0.1	1.1 ± 0.1	0.8 ± 0.1	0.6 ± 0.1
5000	6.2 ± 0.1	4.8 ± 0.1	4.1 ± 0.1	5.1 ± 0.1	3.9 ± 0.1	2.9 ± 0.1	1.4 ± 0.1	1.1 ± 0.1	0.9 ± 0.1
7500	7.8 ± 0.2	6.5 ± 0.3	5.4 ± 0.2	6.7 ± 0.4	4.9 ± 0.1	3.8 ± 0.3	1.8 ± 0.1	1.2 ± 0.1	1.0 ± 0.1
10000	9.5 ± 0.3	7.6 ± 0.4	7.0 ± 0.1	8.2 ± 0.1	5.8 ± 0.1	4.6 ± 0.1	2.2 ± 0.1	1.3 ± 0.1	1.2 ± 0.1

12.7 mm/s = 30 in/min   25.4 mm/s = 60 in/min   38.1 mm/s = 90 in/min



Solidification cracking observed at powers 5kW and above

Defects in laser keyhole welding of IN 740H

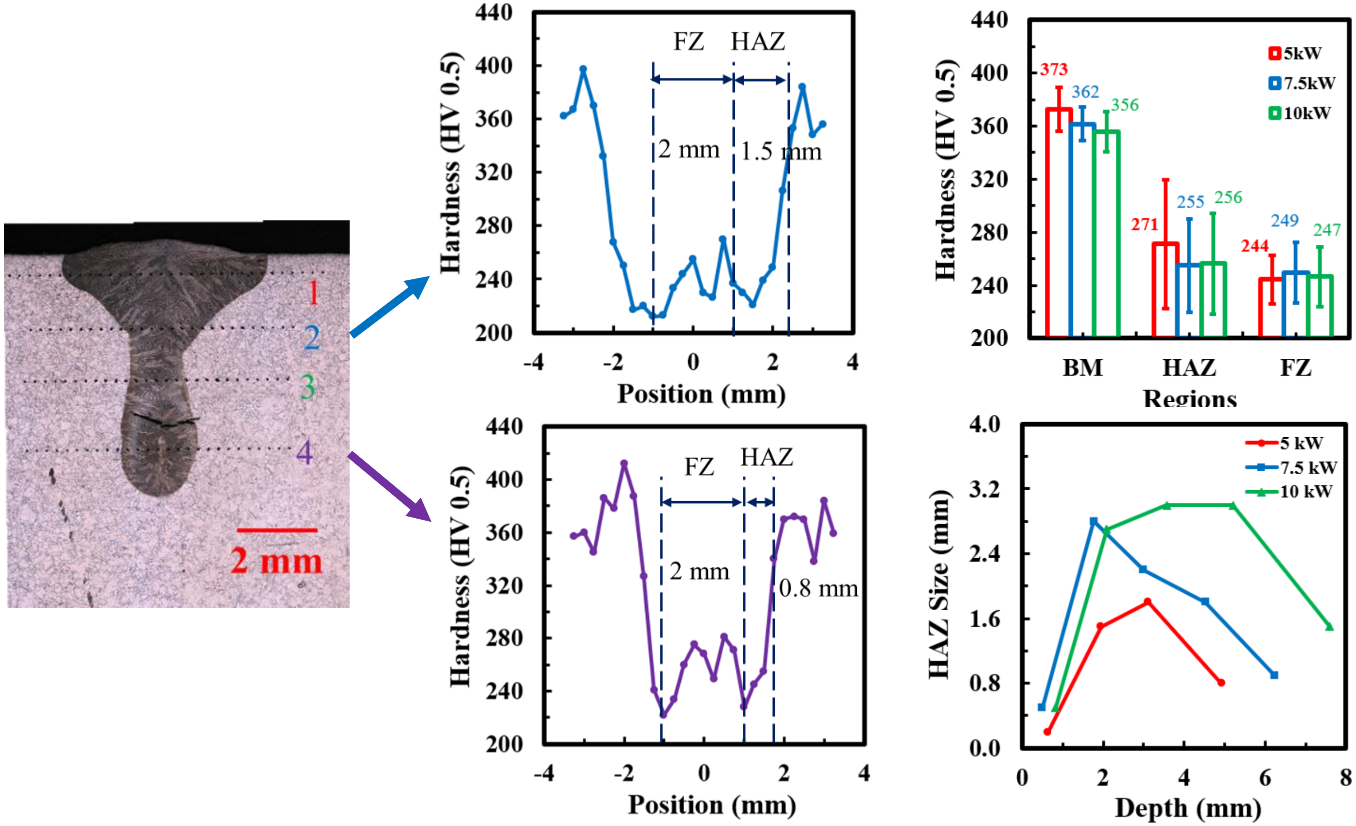


Intergranular solidification cracks observed along weld centerline and around fusion zone boundary

Multiple liquation cracks observed in the HAZ

Keyhole collapse porosity present in higher speed welds

Hardness measurements indicate small HAZ width and softening in the HAZ and FZ

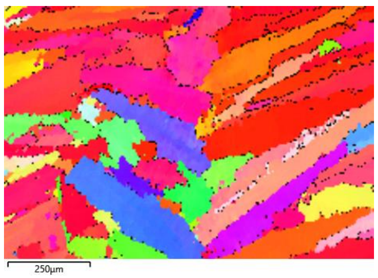


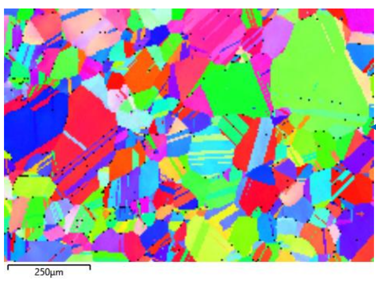
Smaller HAZ width from top to pool bottom

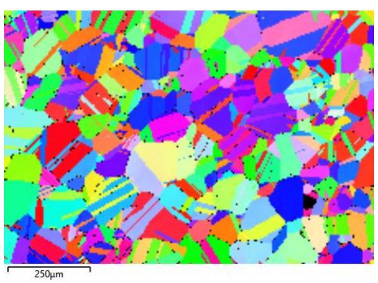
Hardness indicates considerable softening in FZ followed by HAZ

Increasing laser power results in increased softening and increases HAZ width

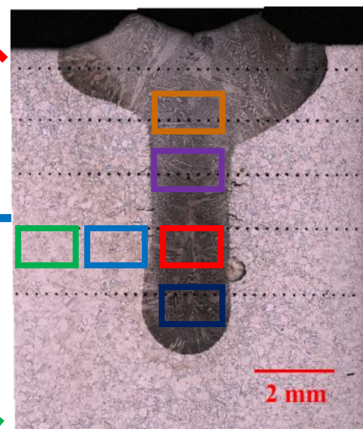
Increasing fine microstructure (with small SDAS) enriched in Nb and Ti with depth

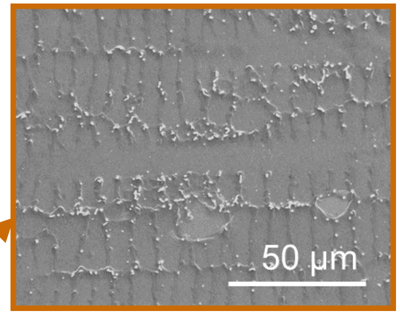


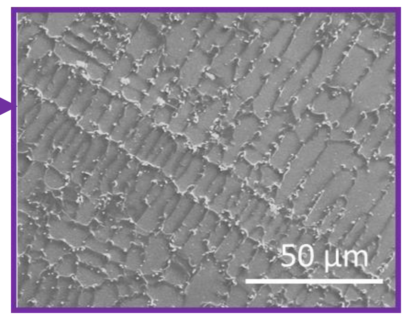


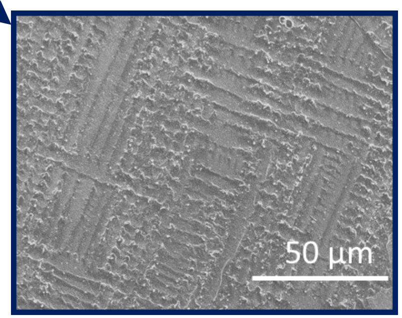


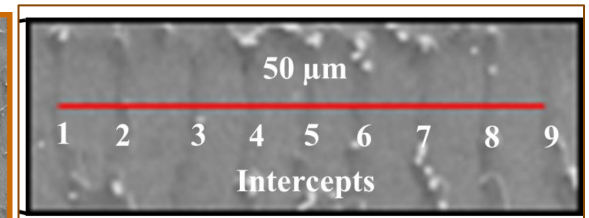
IN 740H 7.5kW,
12.7 mm/s (30 in/min)



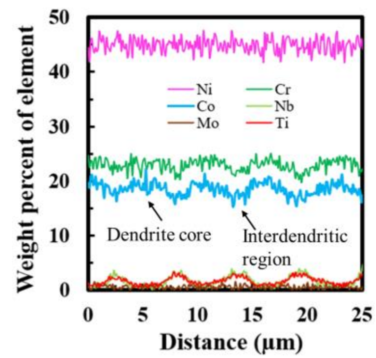








SDAS, λ_2, is related to length of line (L) and number of intercepted dendrites (n) as:

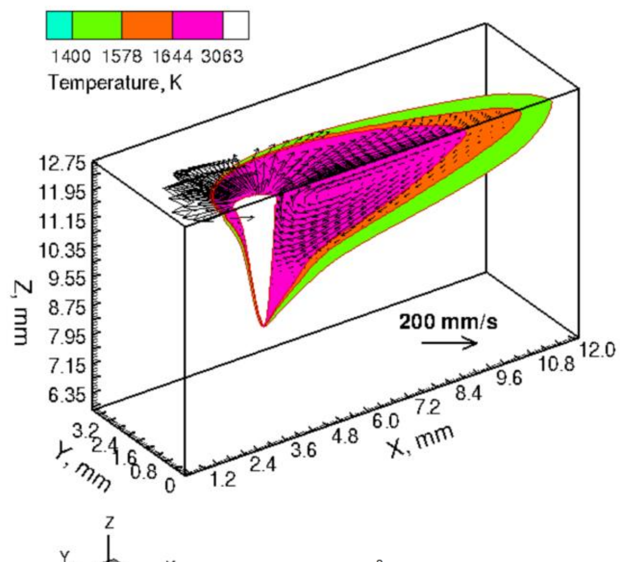


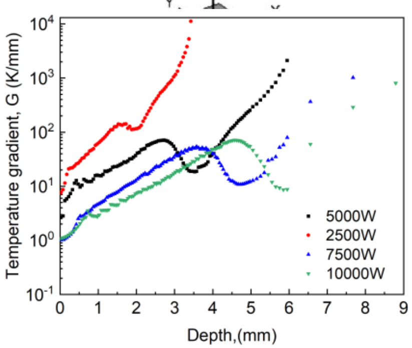
Elements	C_{core}	C_{ID}
Ni	44.9 ± 1.6	45.7 ± 0.8
Cr	23.7 ± 0.8	22.0 ± 1.1
Co	19.7 ± 0.4	17.1 ± 1.1
Nb	0.8 ± 0.5	2.7 ± 0.5
Mo	0.3 ± 0.2	0.2 ± 0.1
Ti	0.9 ± 0.1	2.9 ± 0.4

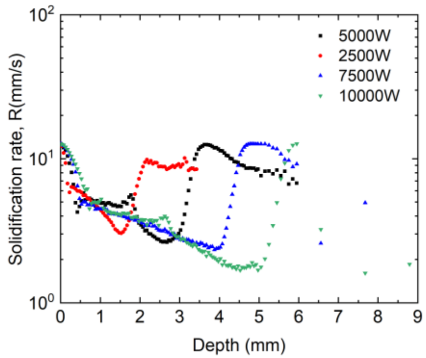
Task 1.C Modeling of Deep Penetration Welding

Three-dimensional temperature and velocity fields for laser keyhole welding of IN 740H

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







Two step model for quasi-steady state keyhole welding

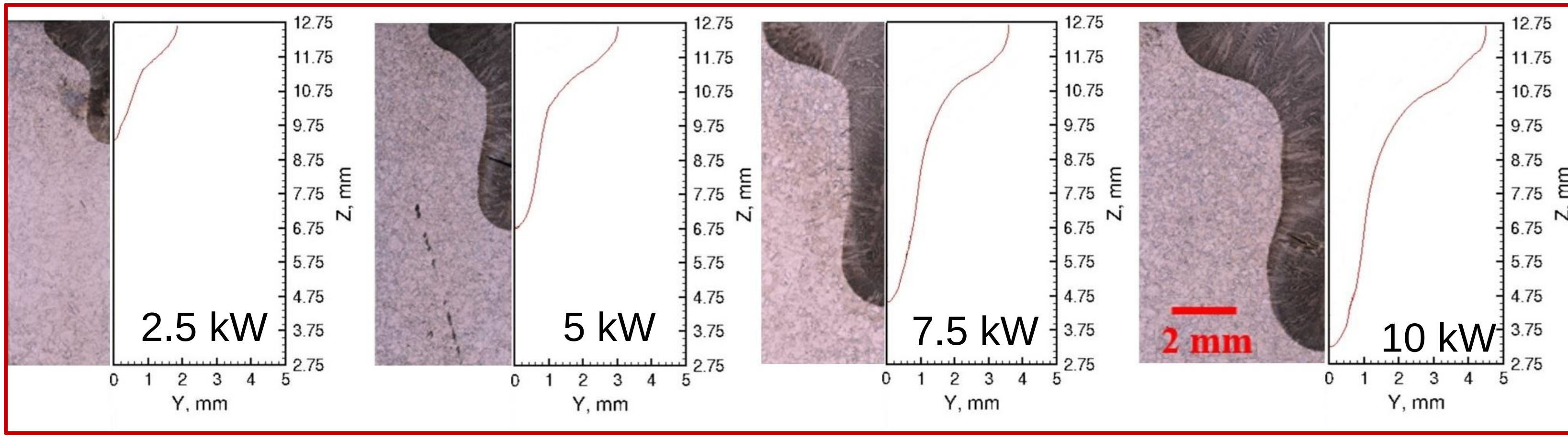
Keyhole profile calculated based on energy balance on keyhole surface which is boiling point the of material

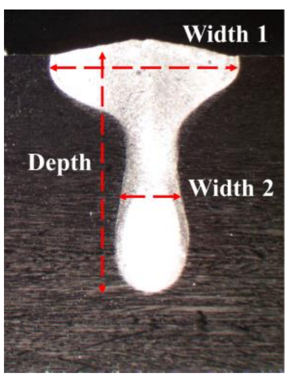
Solve equations of mass, momentum and energy

Thermophysical parameters	**values**
Density (gm/cm^3)	8.2
Solidus temperature (K)	1578
Liquidus temperature (K)	1644
Enthalpy of solid at solidus (J/g)	687
Enthalpy of liquid at liquidus (J/g)	1015
Specific heat of solid (J/g-K)	0.68
Specific heat of liquid (J/g-K)	0.72
Thermal conductivity of solid (W/m-K)	20
Thermal conductivity of Liquid (W/m-K)	32.7
Coefficient of thermal expansion (1/K)	1.0E^{-6}
dY/dT of material (dynes/cm-K)	-0.33
Boiling point (K)	3063

Good agreement between experiment and model

12.7 mm/s (30 in/min)





Laser Power (kW)	Depth (mm)		Width 1 (mm)		Width 2 (mm)	
	Model	Expt	Model	Expt	Model	Expt
2.5	3.3	3.5	3.6	3.6	1.6	1.1
5	6.0	6.1	5.8	5.1	1.9	1.5
7.5	7.7	7.8	7.3	6.7	2.2	1.9
10	9.6	9.7	9.1	8.3	2.4	2.3

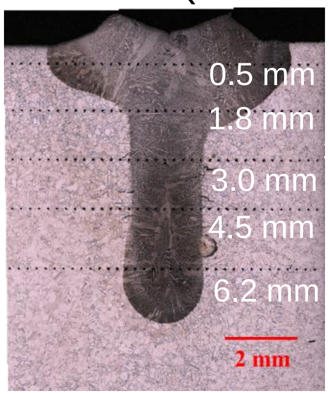
2% error between model and experimental dimension

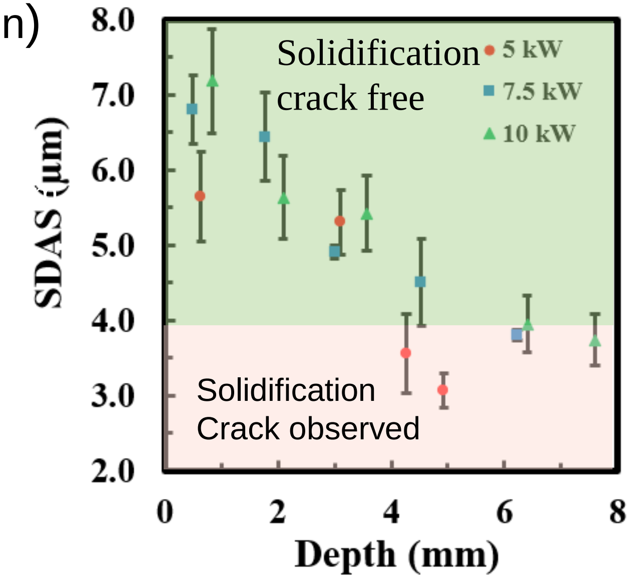
Model accuracy improves at higher laser powers

Task 1.C Appearance of Solidification Cracking at High Laser Powers

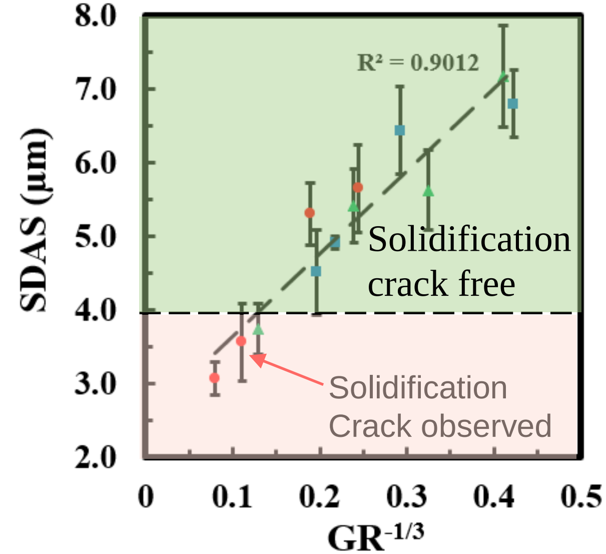
Relation between secondary dendrite arm spacing (SDAS), cooling rate (GR), solidification crack (SC)

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





$$\lambda_2 = b \times (GR)^{-1/3}$$



SC observed at depths between 4 and 6.4 mm for power 5kW-10kW

Increasing GR along depth of pool results in decrease in SDAS

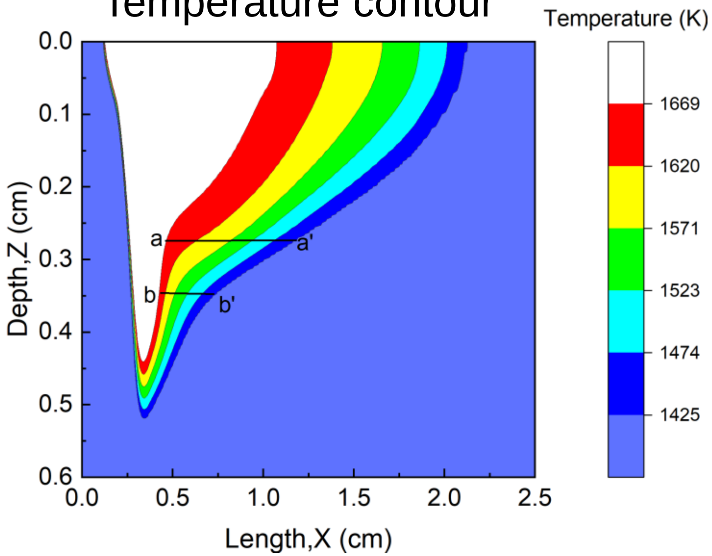
Critical SDAS associated with crack is 4µm and below

Since SC results due to competition between rate of shrinkage (ROS) and rate of feeding (ROF), smaller SDAS indicates difficulty in feeding during last stages of solidification resulting in crack formation

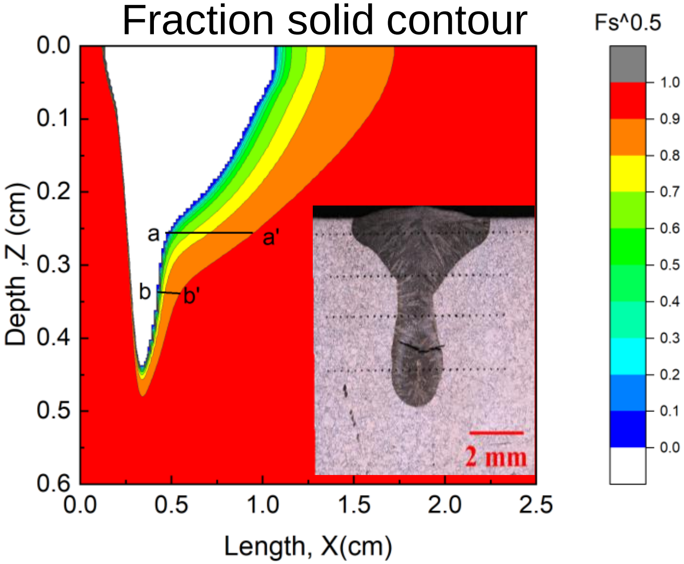
Slope criteria combined with 3D model of keyhole welding enable prediction of crack site

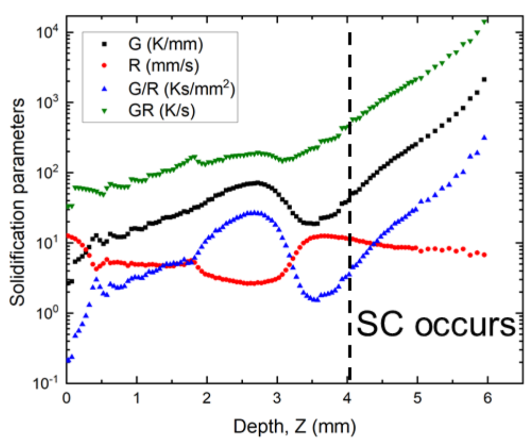
5kW, 12.7 mm/s (30 in/min)

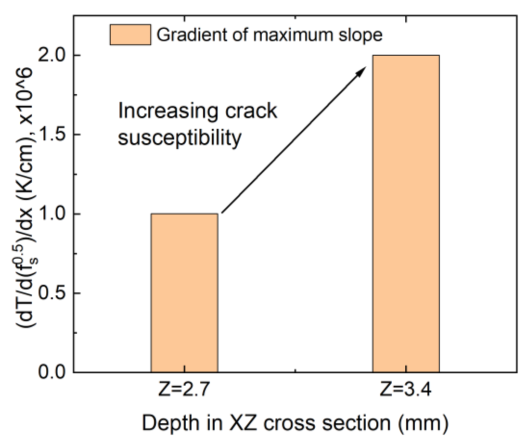
Temperature contour



Fraction solid contour







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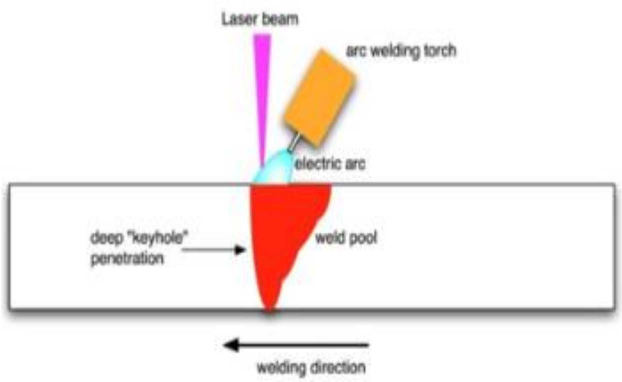
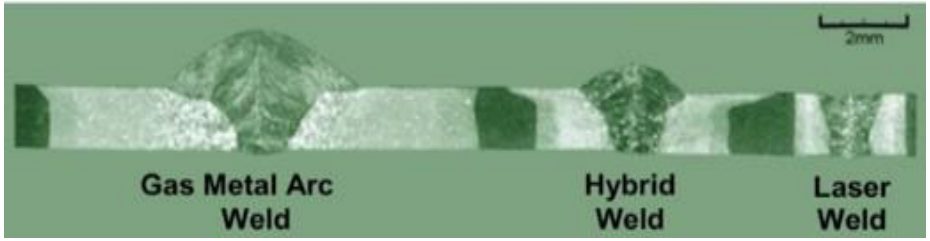
Task 2: Productivity gains during weld groove filling by HLAW

Main Objectives:

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



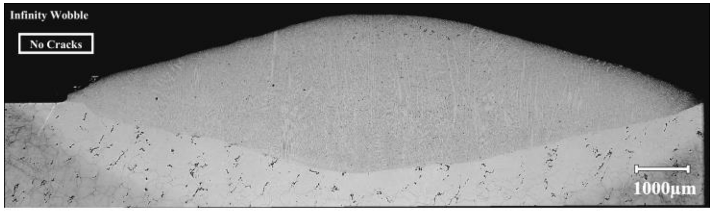


Sub-Tasks:

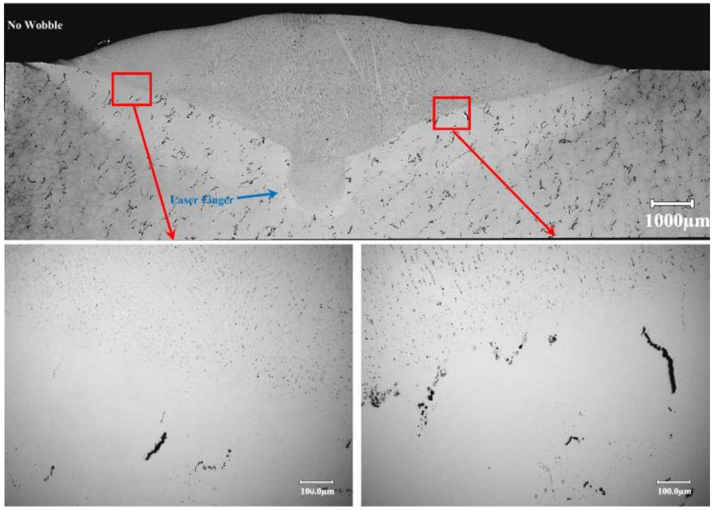
- Single pass, bead-on-plate HLAW study with/without laser wobble
- Multi-pass HLAW with laser wobble weld groove filling

Sub-Task 2A: Single pass, bead-on-plate HLAW study with/without laser wobble

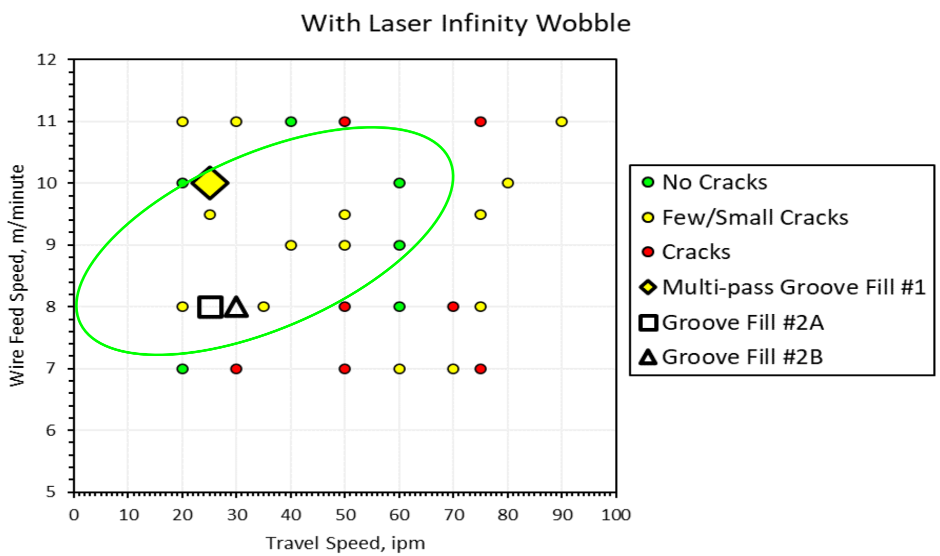
- HLAW welds with/without laser wobble:
  - 3 kW laser power
  - Infinity wobble
  - Travel speed: 50.8 cm/minute → 228.6 cm/minute
  - Wire feed speed (1.14 mm dia): 7-11 m/ minute (3.4 kg/hr → 5.4 kg/hr)



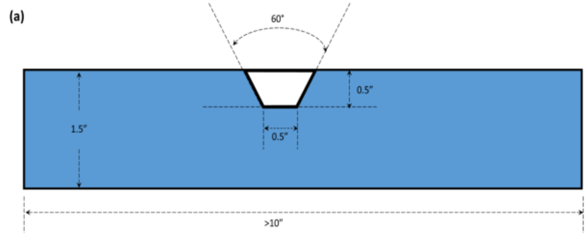
Wobble pattern	Laser Energy, kW	Travel Speed, cm/minute	Wire Feed rate,, m/minute	Deposition rate, kg/hr
Infinity	3	50.8	7	3.4



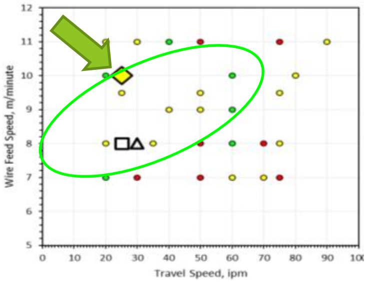
Wobble pattern	Laser Energy, kW	Travel Speed, cm/minute	Wire Feed rate,, m/minute	Deposition rate, kg/hr
No wobble	3	50.8	7	3.4

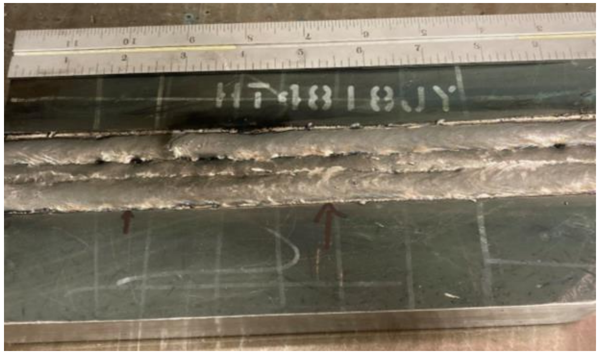


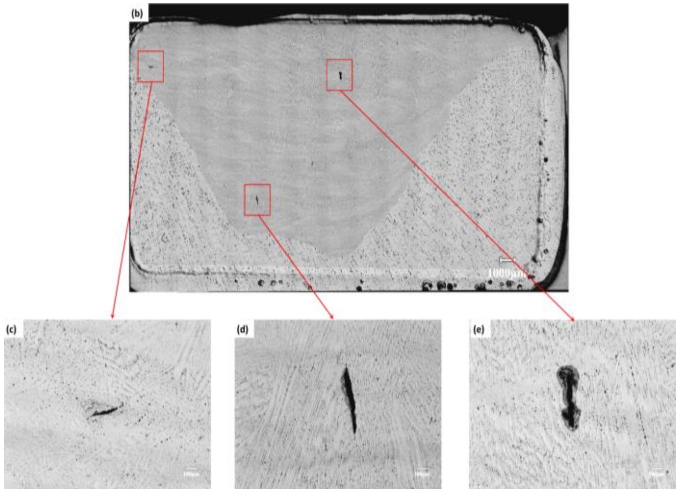
Sub-Task 2B: Multi-pass HLAW with laser wobble weld groove filling



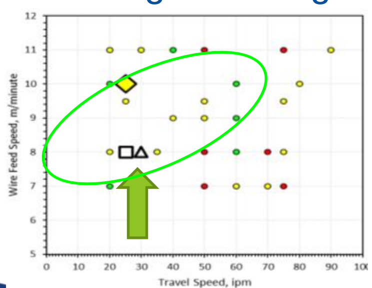
1st groove filling campaign
(60° groove angle)







2nd groove filling campaign
(60° & 45 °groove angles)



Characterization underway

Summary and Conclusions

- Metallurgy of Alloy 740H and welding parameters contributes/controls to liquation cracking at high welding speeds/rates
- Laser wobble reduces propensity for cracking
- Modeling and simulation will provide insights to:
  - laser welding parameters for deep penetration laser welding of thick weld groove lands
  - HLAW weld groove filling
- Single pass, bead-on-plate study helps define HLAW processing parameter window
- Optimization of HLAW parameters for multi-pass weld groove filling is underway

Contact Information:

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