Advancements in Thick Titanium FSW

John Hunt
CTC

About the Presenter

- Johnathon Hunt, PhD
  - Engineering Project Manager
- Defect Detection in FSW, RFSSW, Cost Analysis of FSW
- Co-Authors
  - Martin McDonnel, US Army
  - Kenneth Ross, PNNL
  - Christopher Smith, PNNL
- We confirm there is not conflict of interest within this presentation

Pacific Northwest NATIONAL LABORATORY

U.S. ARMY

CTC Concurrent Technologies Corporation

Presentation Overview

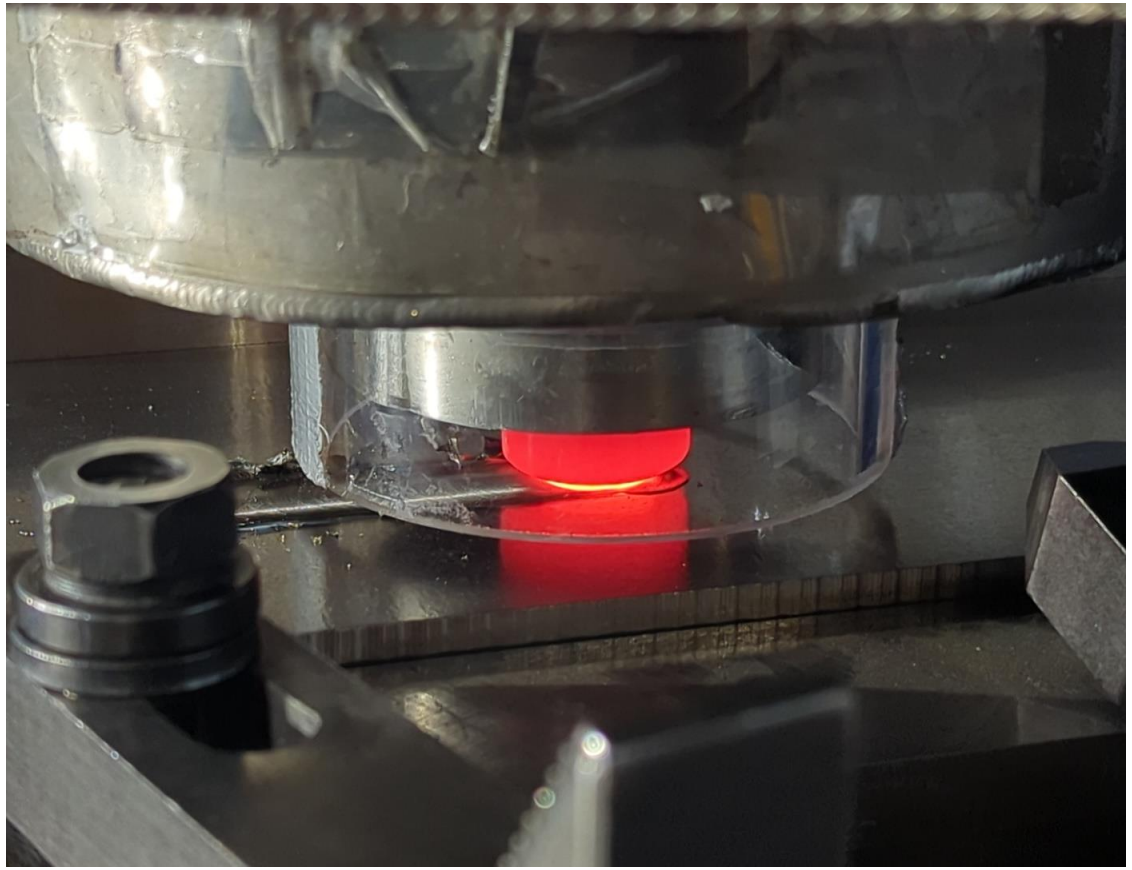
- Brief titanium FSW overview
- Experiment background
- Results & Discussion
- Conclusions
- Questions

OVERVIEW


THE WORLD COMES HERE.
TMS2025
154th Annual Meeting & Exhibition
TMS 2025 154TH ANNUAL MEETING & EXHIBITION
www.tms.org/TMS2025 · #TMSAnnualMeeting
Fabulous
LAS VEGAS
NEVADA

Brief Titanium FSW Overview

- Titanium FSW has been an active area for over 20 years
- Two main phases are present in most titanium alloys
  - HCP alpha phase
  - BCC beta phase
- Beta transus temperature is a critical during FSW
- Thickest FSW titanium documented is 25 mm thick



EXPERIMENT BACKGROUND

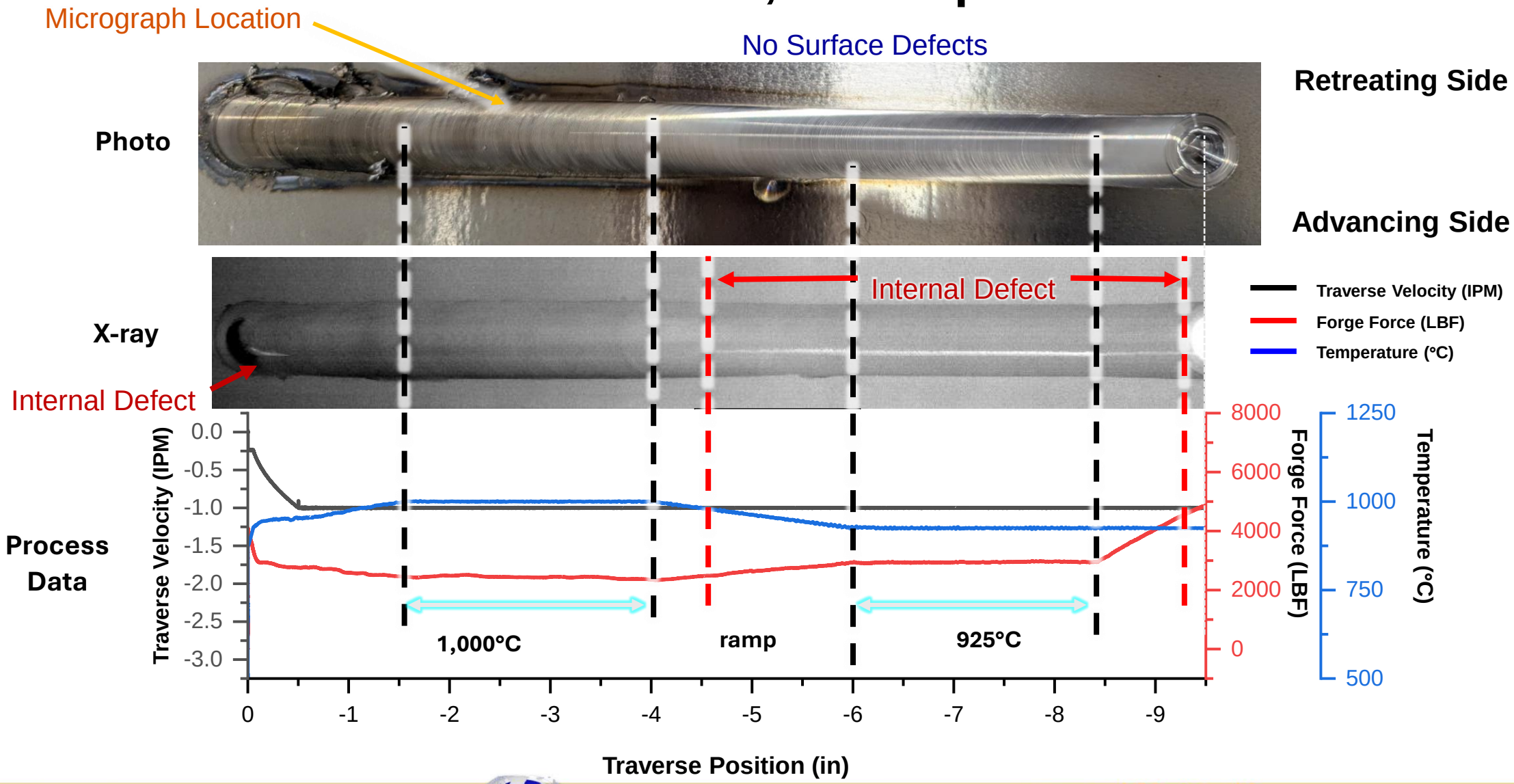
Experiment Background

- **Material: 6.35 mm thick Ti6Al4V**
- **Temperatures:**
  - **700° C (25 MMPM)**
  - **775° C (25 MMPM)**
  - **850° C (25 & 76 MMPM)**
  - **925° C (25 & 76 MMPM)**
  - **1,000° C (25 & 76 MMPM)**
  - **Gains tuned for 25 MMPM**
- **Machine: PNNL TTI**
- **Tool: WLa**

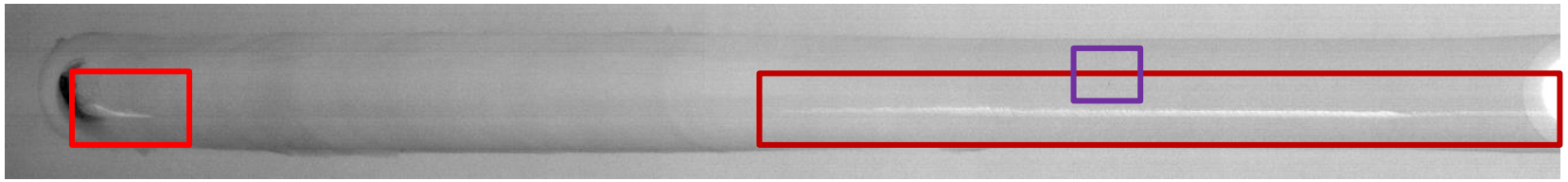
Ungrounded thermocouple silver soldered at tool-workpiece interface

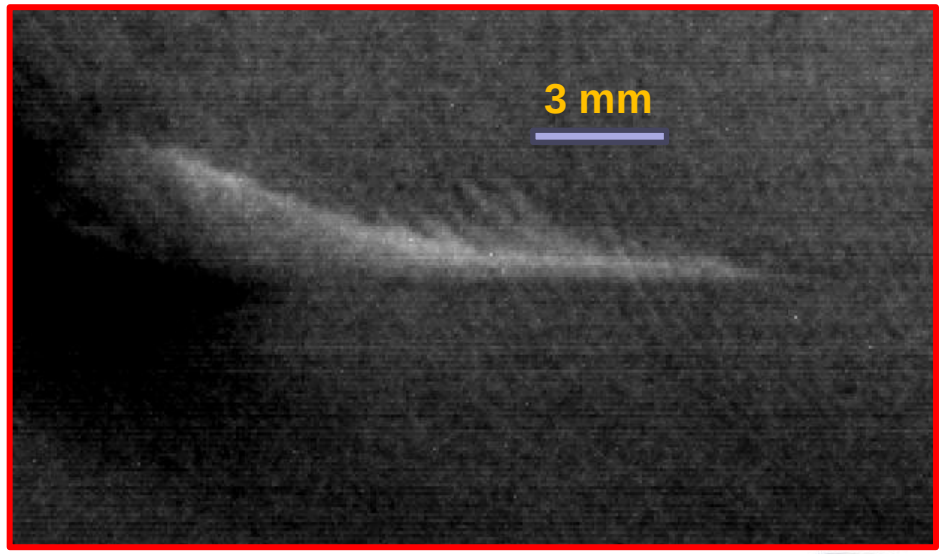
RESULTS & DISCUSSION

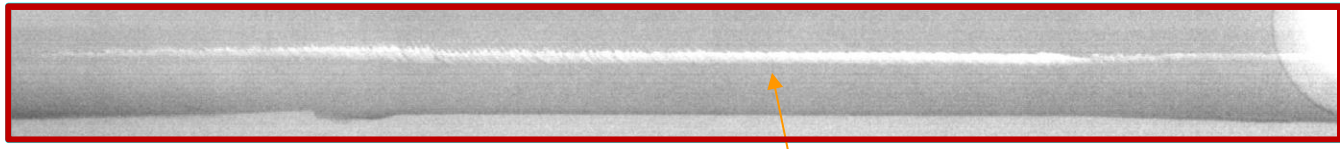
2025 03 10 0007 High T, Position Control, 25 mmpm



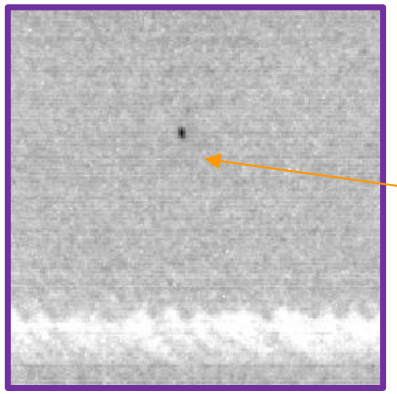
2025 03 10 0007 High T, Position Control, 25 mmpm







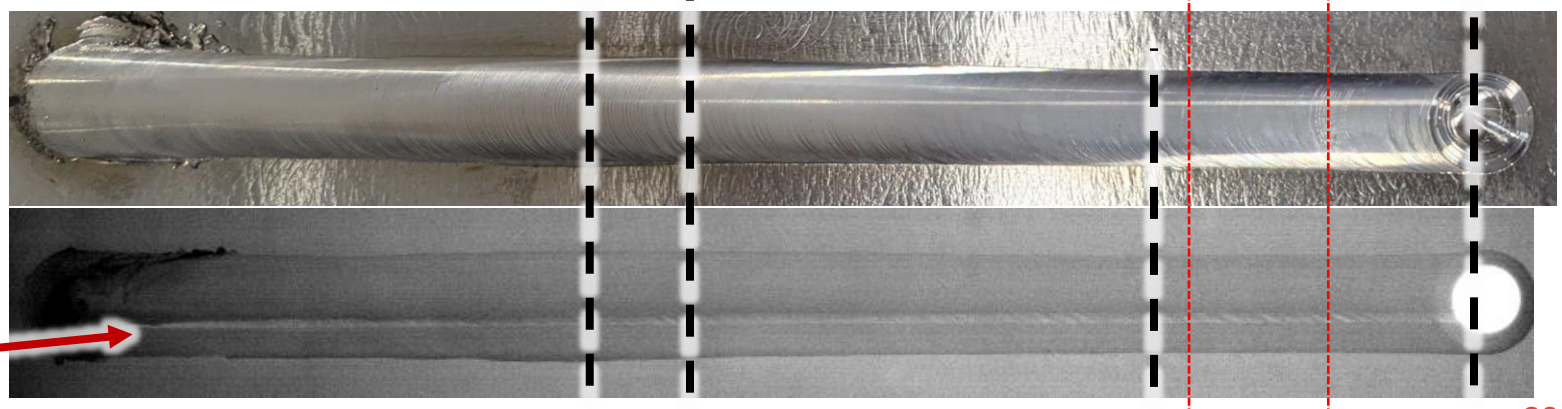
Void along weld direction:
L x W = 132 x 1 mm



200 µm diameter
High-density inclusion

2025 03 10 0008 High T, Position Control, 76 mmpm

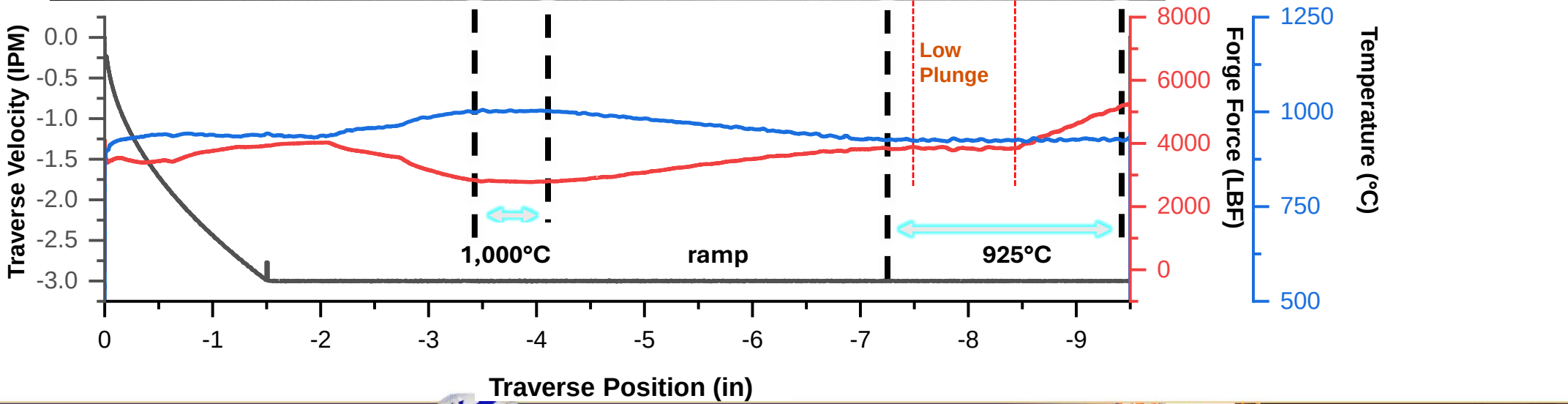
No Surface Defects



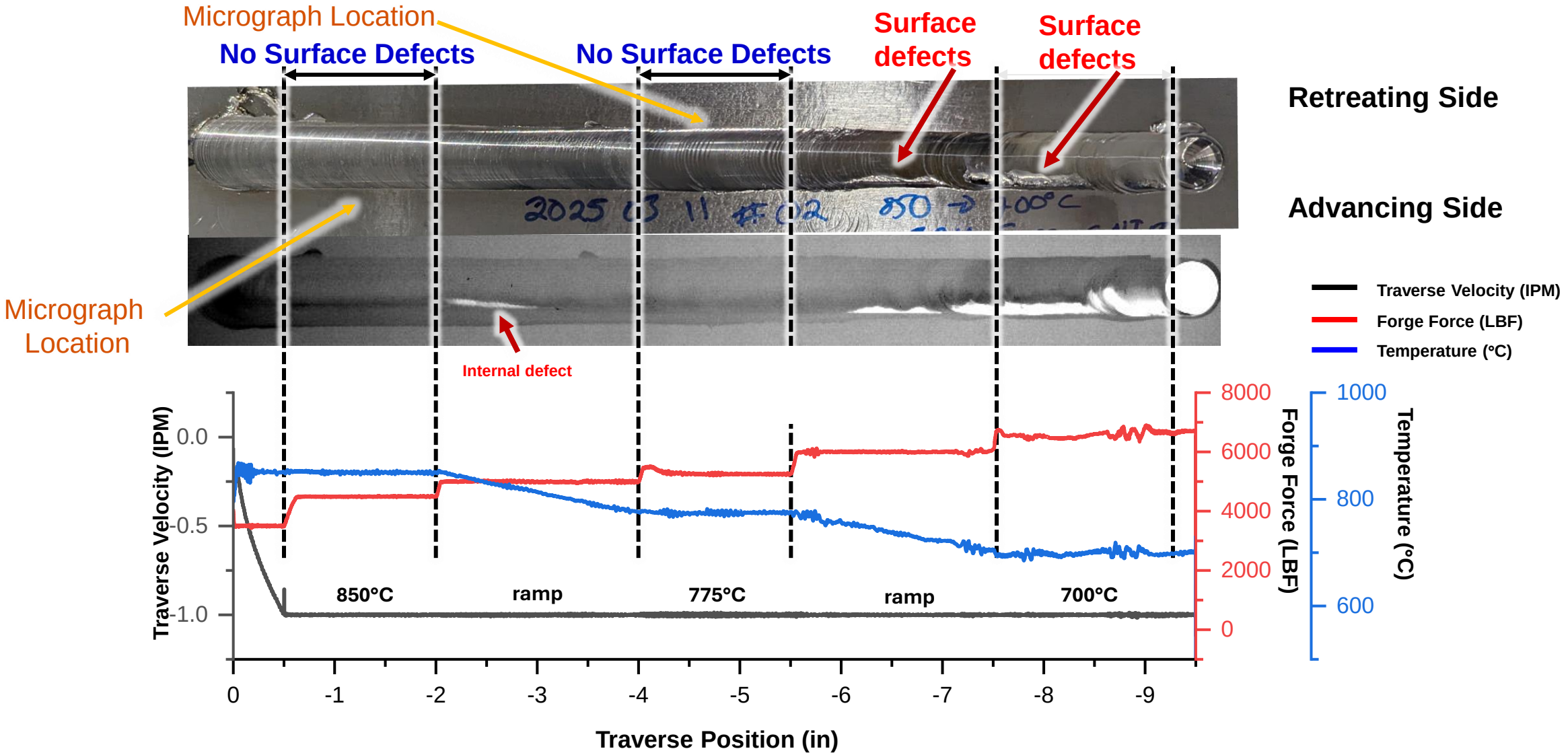
Retreating Side

Advancing Side

Internal defect along entire length

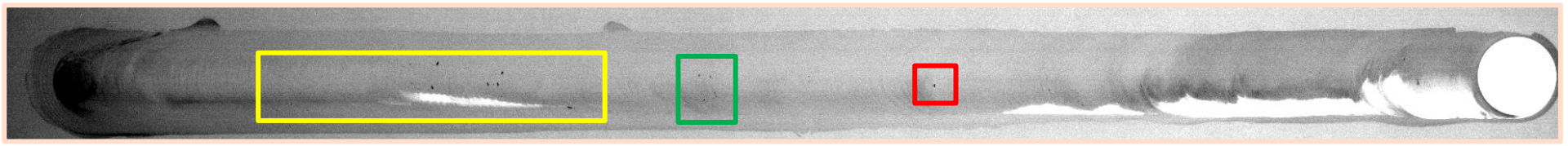


2025 03 11 0003 Low T, Force Control, 25 mmpm

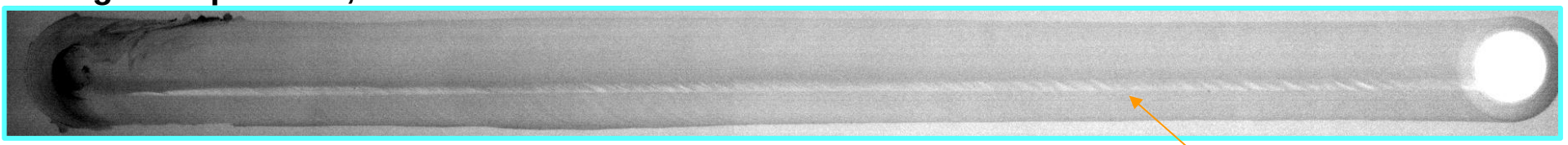


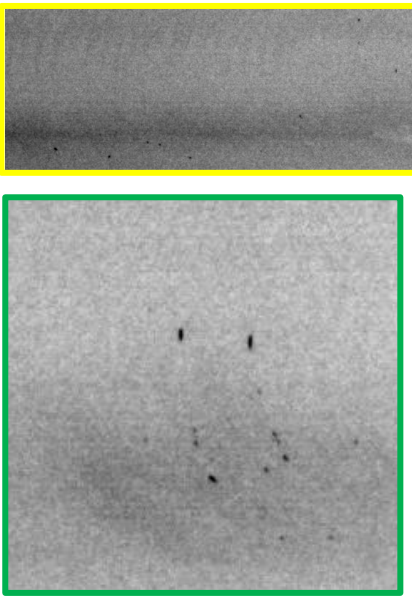
Low Temperature 25 MMPM & High Temperature 76 MMPM

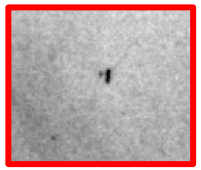
Low Temperature, Force Control



High Temperature, Position Control





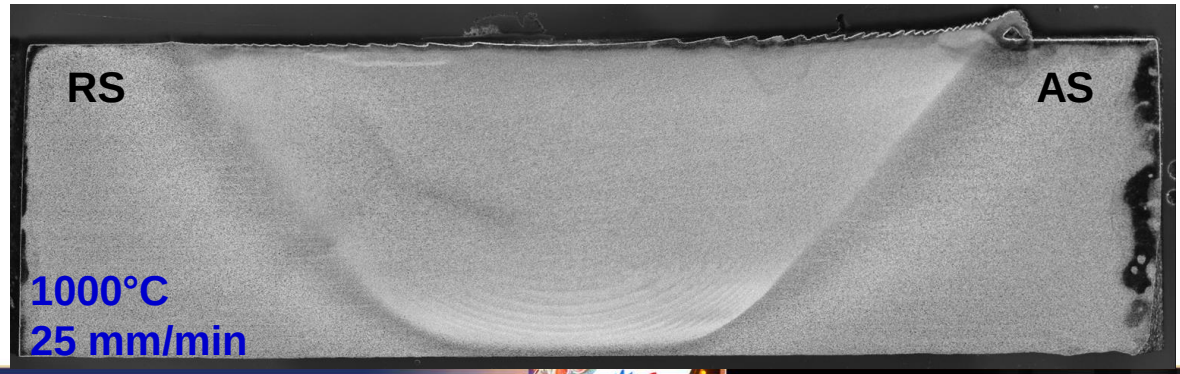


Spurious high-density inclusions along length of weld varying between 100-300 µm diameter

Weld #08 ~free of high-density inclusions. Void along length of weld, width of 400-2000 µm

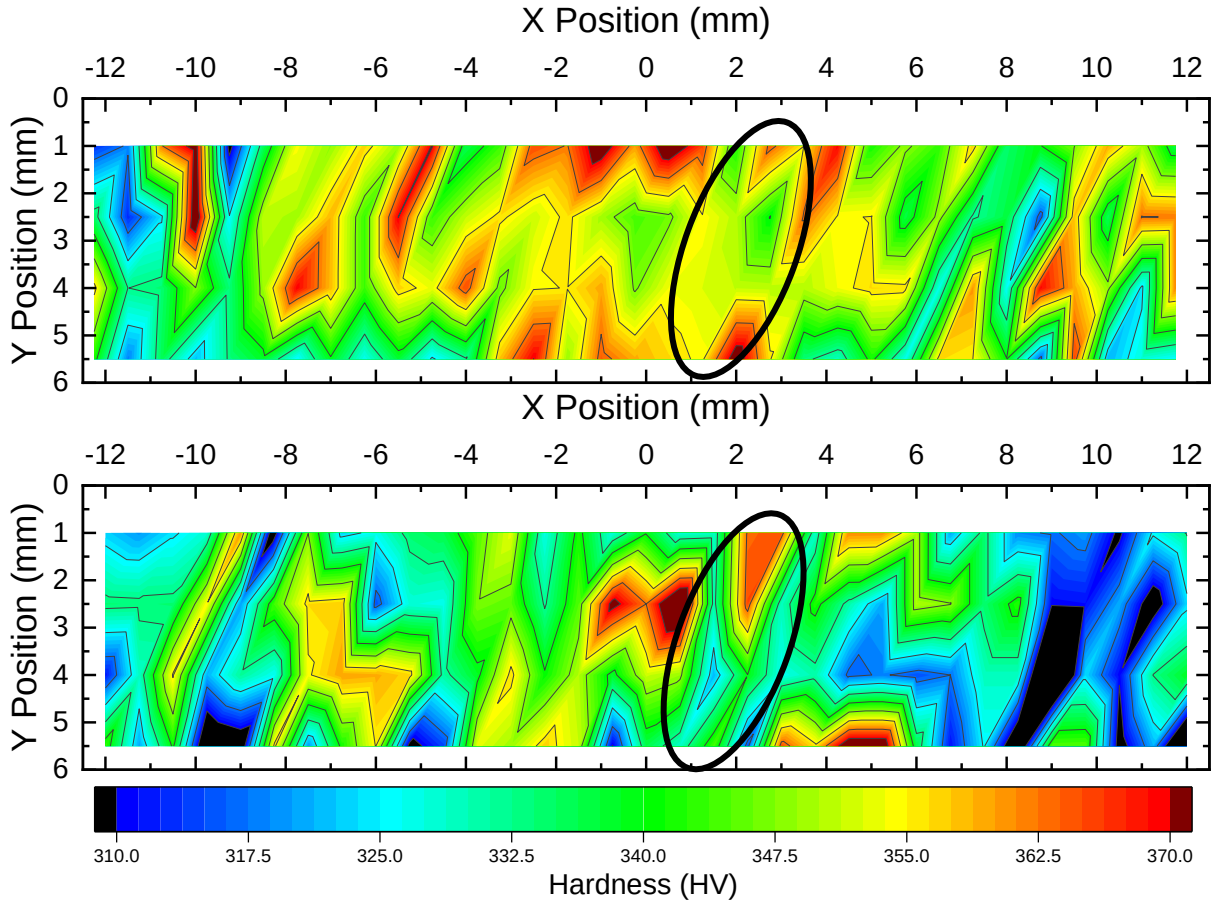
Optical Microscopy

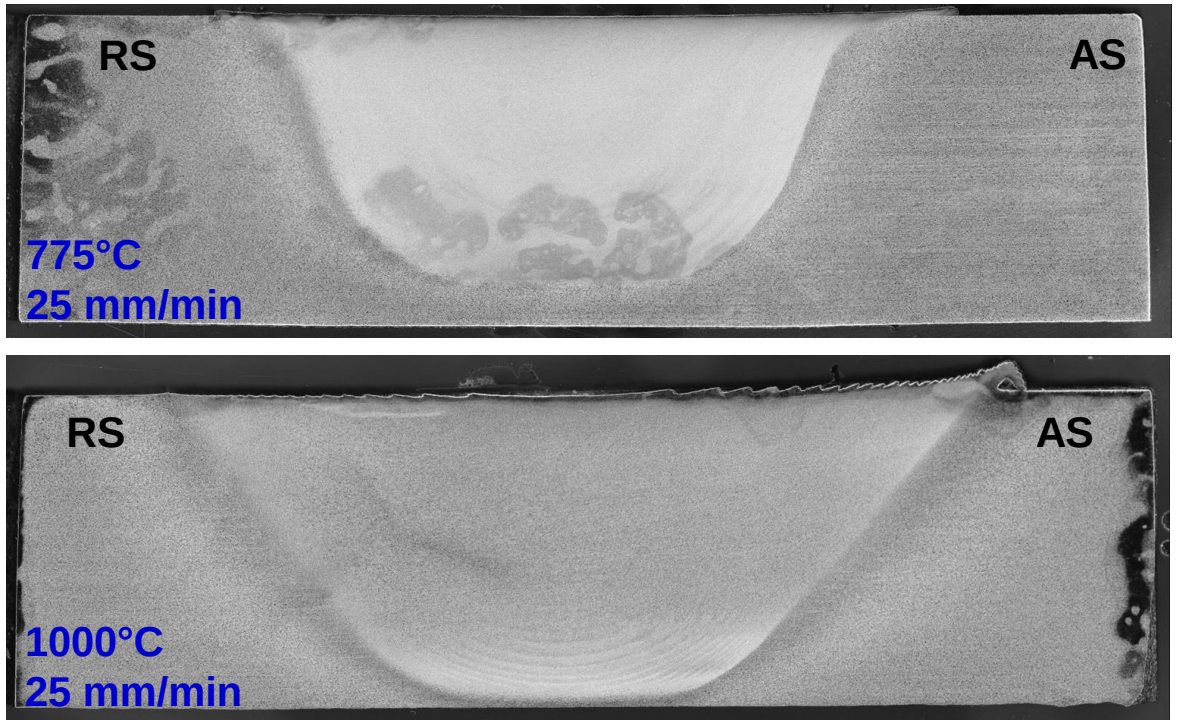
5 mm



Micro Hardness

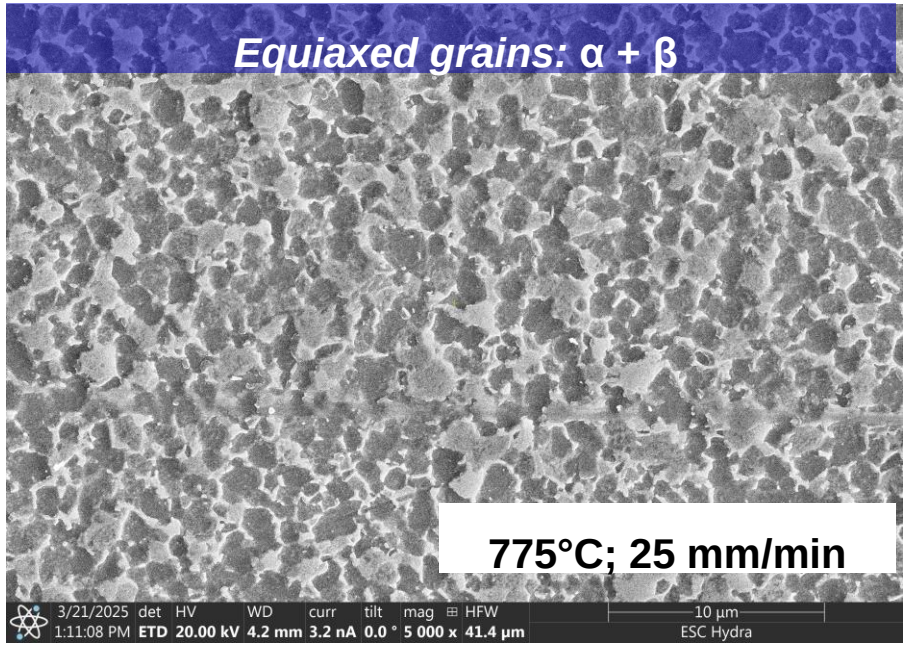
Base Material Hardness Average is 317.24 (HV)



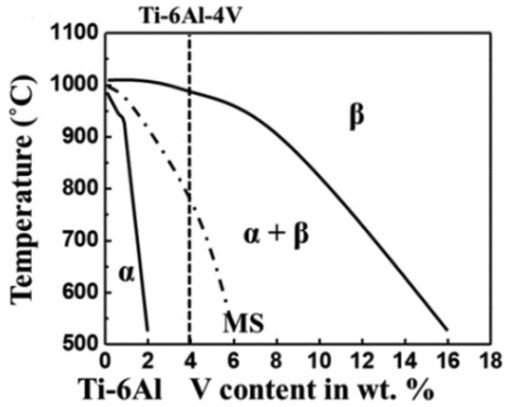


- **Average sample hardness decreases from 347.2 HV to 334.6 HV. The biggest difference is in the hardness of the heat affected zone particularly on the advancing side of the FSP region.**
- **The stir zone hardness decreases from 353.1 HV to 341.7 HV as temperature increases from 775°C to 1000°C.**

Equiaxed grains: α + β

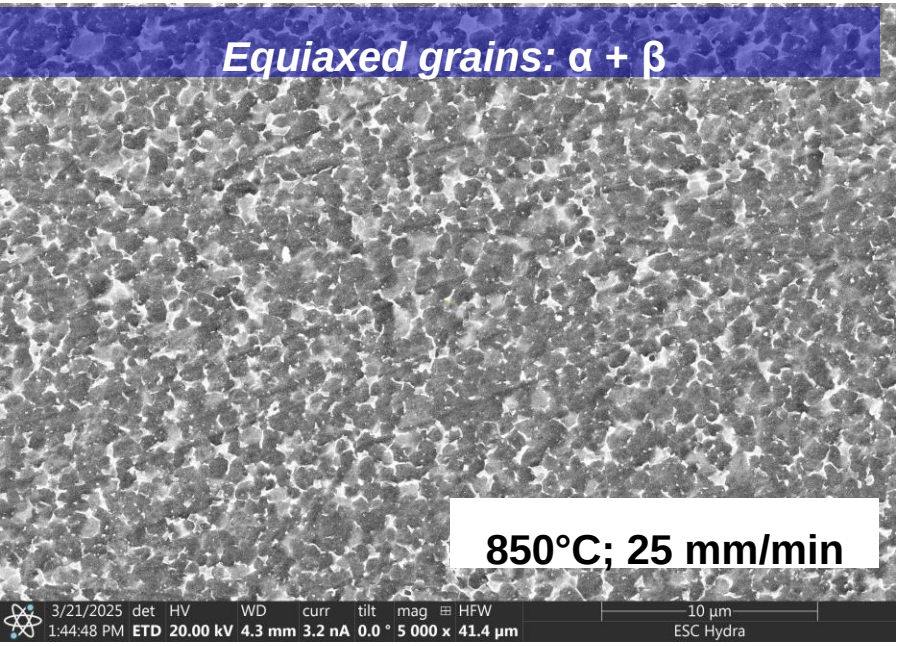


Phase Diagram of Ti64 Alloy

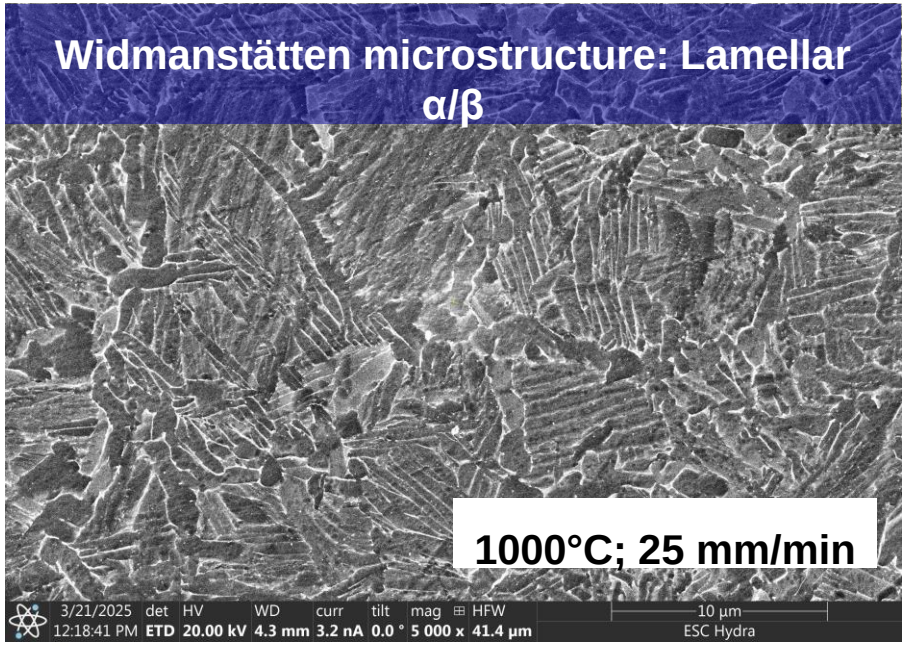


All images are from the stir zone

Equiaxed grains: α + β



Widmanstätten microstructure: Lamellar α/β



- Phase Contrast in SEM Imaging: The darker regions correspond to the α-phase, while the brighter regions represent the β-phase.
- Microstructural Evolution at 1000°C:
  The sample processed at 1000°C exhibits a distinctly different microstructure compared to the other two conditions. This divergence arises because temperatures above the beta transus (~1000°C) induce complete transformation of the material into the β-phase during friction stir processing (FSP). Subsequent rapid cooling (post-FSP quenching) suppresses equilibrium phase formation, resulting in a lamellar microstructure dominated by fine α/β laths.

Tool Wear

New Tool

5 mm

Tool after running 750 and 700°C as measured at the tool-workpiece interface

- Significant wear and deformation observed in low temperature welds (<850°C)
- Negligible wear and deformation observed after >850°C welds.

Study Cost

Temperature Control	
No. Welds	2
No. FSW Tools	1
Pre-Weld Machining hrs	2
Welding Time hrs	3
Post-Weld Machining hrs	2
Metallography hrs	4

DOE Full Factorial 1x Replicate	
No. Welds	8
No. FSW Tools	3
Pre-Weld Machining hrs	3
Welding Time hrs	12
Post-Weld Machining hrs	5
Metallography hrs	10

Roughly 2.85x more expensive

Conclusions

- **Temperature control & X-ray imaging saved a significant amount of time & money in development**
- **Slower Welding Speeds were more robust**
- **Tool Life is dramatically reduced at lower welding temperatures**
- **Temperature control can control the microstructure within the stir zone**
- **Future work:**
  - **Tool wear studies**
  - **Mechanical property tests**
  - **Continued work in faster welding speeds**

THANK YOU


THE WORLD COMES HERE.
TMS2025
154th Annual Meeting & Exhibition
TMS 2025 154TH ANNUAL MEETING & EXHIBITION
www.tms.org/TMS2025 · #TMSAnnualMeeting
Fabulous
LAS VEGAS
NEVADA

QUESTIONS


THE WORLD COMES HERE.
TMS2025
154th Annual Meeting & Exhibition
TMS 2025 154TH ANNUAL MEETING & EXHIBITION
www.tms.org/TMS2025 · #TMSAnnualMeeting
Fabulous
LAS VEGAS
NEVADA

Appendix

General Process Parameters

- **Tilt Angle – 2°**
- **Argon Enabled – Quartz Shield**

Experiment Summary

Weld No.	Rotation Rate (RPM)	Power (kW)	Temperature (°C)	Traverse (ipm)	Z Force (N)	Notes
2025 03 07 0002	220	2.57	995	1	14,600	No defects, but some overheating and temperature drifting upwards.
2025 03 07 0003	200	2.56	930	1	15,000	No defects, but some overheating and temperature drifting upwards.
2025 03 07 0004		2.05		1		Power Control with tuned plunge. No defects.
2025 03 07 0007	220	2.05	700 – 745	1	20,727	Relay tuning weld. Did not work due to temperature drifting higher. Defect on weld exit hole.
2025 03 07 0008	~140/200	2.05	881/980 after error	1	21,300 – 14,450	Power control to temperature control using stainless steel gains. Did not work. Hit RPM limit on T start.
2025 03 08 0002						
2025 03 08 0003						
2025 03 08 0004						
2025 03 08 0005						
2025 03 08 0006						
2025 03 08 0007						
2025 03 10 0003						
2025 03 10 0004						
2025 03 10 0005						
2025 03 10 0006						
2025 03 10 0007				1		
2025 03 10 0008				3		
2025 03 11 0003			850 – 700	1	20,000 - 30,024	Force Control

Weld Quality Summary

- 700°C 1IPM surface & wormhole (force control)
- 775°C 1IPM defect free (position control)
- 775°C 1IPM defect free (force control)
- 850 C 1IPM defect free (position control)
- 850 C 1IPM defect free (force control)
- 925°C 1IPM wormhole (position control)
- 925°C 3IPM wormhole (position control)
- 1000°C 1IPM defect free (position control)
- 1000°C 3IPM wormhole (position control)

Weld Quality Summary

I have made a rough cost structure for a DOE with three variables vs Temperature control exploration. Assumptions with this comparison include:

- Temperature Control material and hours
  - 2x welds 9.5” long
  - 1x tool
  - Pre- weld machining time - 1
  - Welding time - 3
  - Post Weld machining - 2
  - Metallography – 4
  - Total Cost $3655
- Without Temperature Control material and hours
  - 8x welds 5” long
  - 3x tool
  - Pre- weld machining time - 3
  - Welding time - 12
  - Post Weld machining - 5
  - Metallography – 10
  - Total Cost $10,437

Material wise I noted that the plate would be 2x more expensive, tooling was 3x more expensive and then put some decent market hours for machine + personnel costs.

Recording and Photography Policy

- Any recording of session presentations, posters, and exhibitor booth displays and/or products (audio, video, still photography, etc.) without express consent by TMS as well as the presenter or the exhibitor is strictly prohibited.
- This prohibition includes the taking photos of slides during presentations or demonstrations unless express consent is given by the presenter.
- As a presenter, you may give permission to the audience at the start of your presentation or by adding a note on slides that you allow to be photographed.
- Attendees violating this policy may be asked to leave the session, the conference, or the TMS membership.
- Outside of presentation and exhibitor settings, conference attendees may record or photograph other attendees provided that the individual(s) being recorded or photographed provide explicit permission to be recorded or photographed and the specific event venue is not otherwise specified as a recording-/photography-free zone.