Pacific Northwest
NATIONAL LABORATORY

Integrated Process Improvement Using Laser/Friction Stir Processes for Nickel Alloys Used in Fossil Energy Power Plant Applications

Glenn Grant and Chris Smith
Jens Darsell, Mageshwari Komarasamy, Woongjo Choi
Pacific Northwest National Laboratory

Anand Kulkarni and Kyle Stoodt
Siemens Corporation, Charlotte, NC

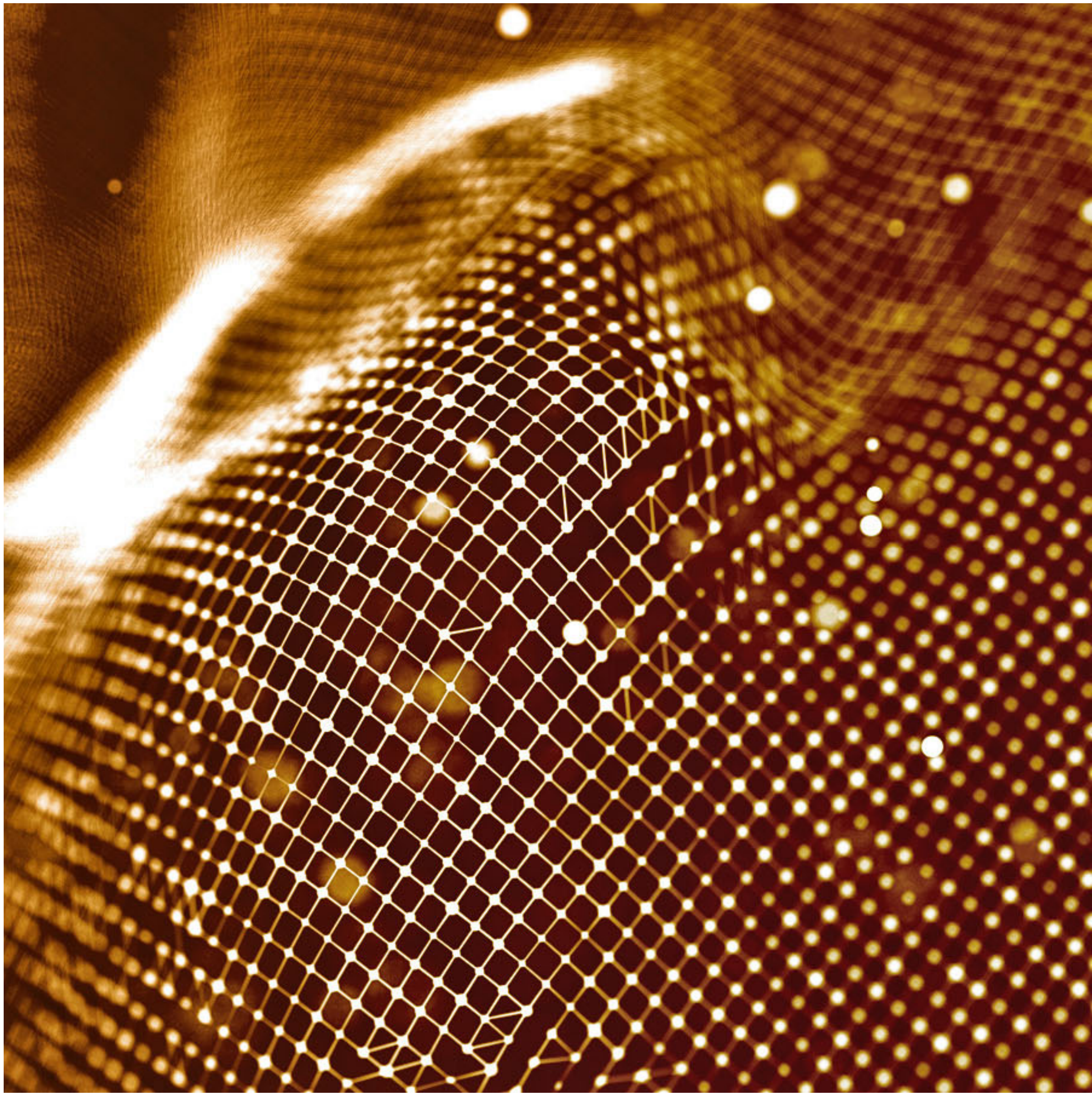
Paul Jablonski
NETL Albany

U.S. DEPARTMENT OF ENERGY BATTELLE

PNNL is operated by Battelle for the U.S. Department of Energy

PNNL-SA-172766

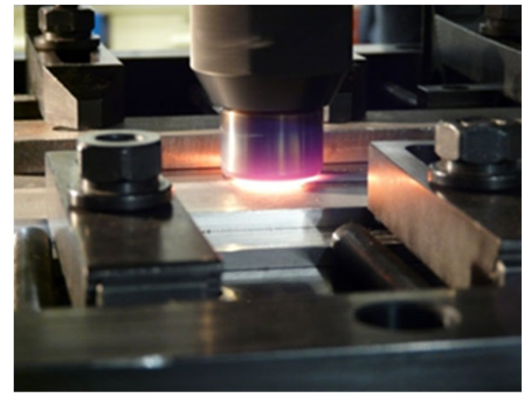
May 9, 2022



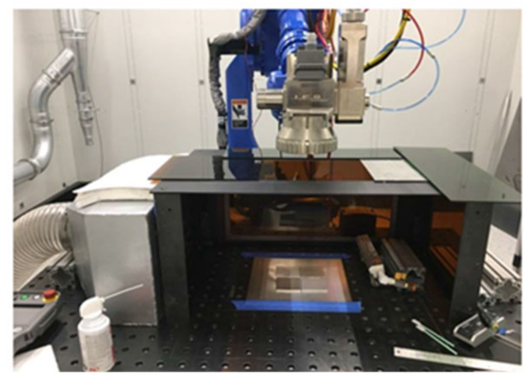
Vision and Project Objective

Vision: Development of new advanced manufacturing processes to reach higher efficiency and lower cost in power generation systems for OEM components, as well as for repair and refurbishment.

Objective: Investigate and demonstrate an integrated approach using both Laser Processing (LP) and Friction Stir Welding and Processing (FSW/P) to fabricate and repair Nickel based super alloys



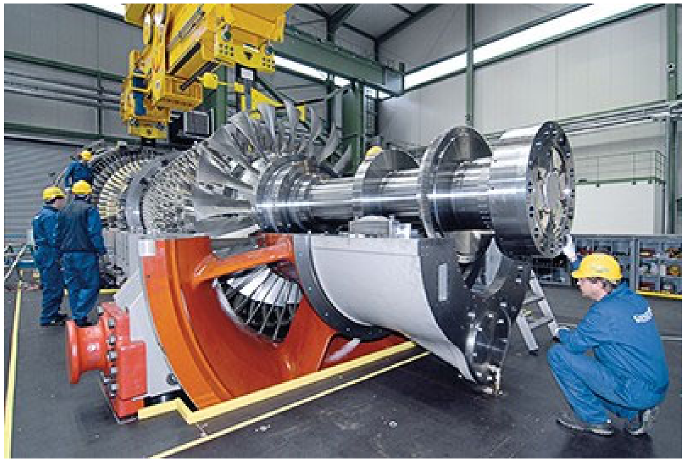
FSW of High Melting Point Material at PNNL



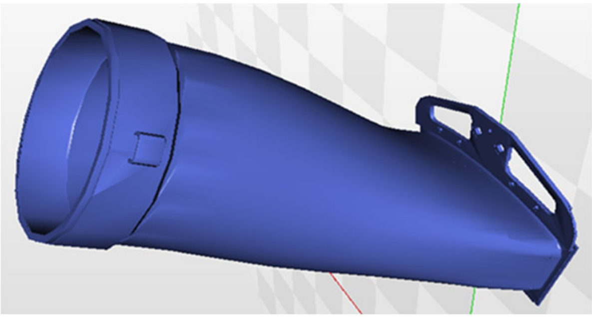
Robotic Laser Ablation System
Courtesy: IPG Photonics

Background

- Fabrication challenges
  - Cycle time and cost of diffusion bonding (DB)
    - Surface preparation needed for DB (and for later application of thermal barrier coatings),
  - Hot cracking / liquation cracking with fusion welding
  - For large Ni alloy castings near surface casting defects.
- Repair challenges
  - In-service degradation of Thermal Barrier Coatings (TBC) requires time consuming stripping/ cleaning of the TBC prior to recoating.
  - Crack or damage repair by fusion welding or overlay processing leads to hot cracking during weld repair



Transition Duct
Courtesy: www.siemens.com/press



Transition Duct
Courtesy: Siemens

Approach & Major Tasks

- Laser Processing - Siemens Lead
  - Investigate laser ablation (LA) of TBC bond coat for repair/return to service
  - Laser ablation as a surface treatment to enhance diffusion bonding

- Friction Stir Welding / Processing (FSW/P) - PNNL Lead
  - Compare FSW/P to diffusion bonding and fusion welding processes
  - Investigate FSW to achieve high performance joints in nickel superalloys
    - Haynes 282, 233 and Inconel 617
  - Discover the effect of FSW parameters and PWHT on creep

Approach & Major Tasks

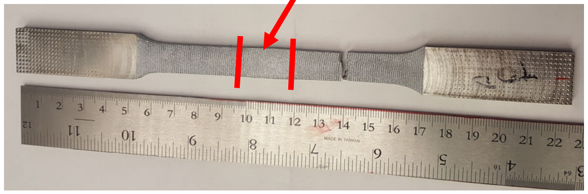
- Friction Stir Processing (FSP) – PNNL Lead
  - For surface treatment or repair (PNNL)
  - Demonstrate ability to repair defected or damaged Ni alloy Castings
  - Demonstrate method to produce local improvements in creep
  - Demonstrate ability to prepare a surface for bond coat/TBC

Haynes 282 Properties vs. FSP Conditions

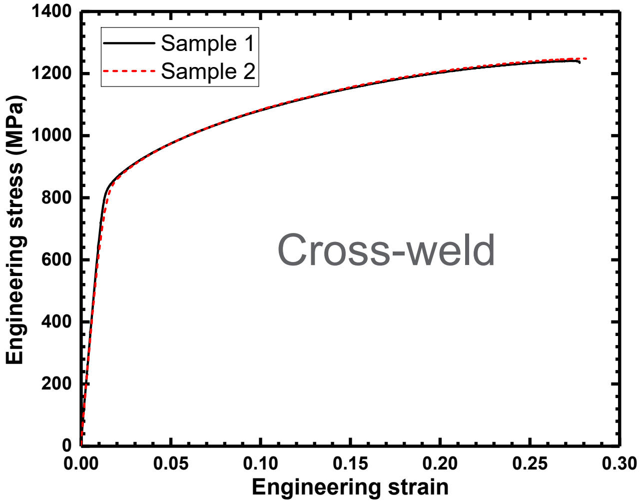
- Cross-Weld Tensile Test
  - After Solution Anneal + 2 Step Heat Treatment
  - Performed at Room Temperature
  - Test parallel to rolling direction
  - Plastic deformation initiated in base metal
  - Failure in base metal
  - Nugget deformation also present

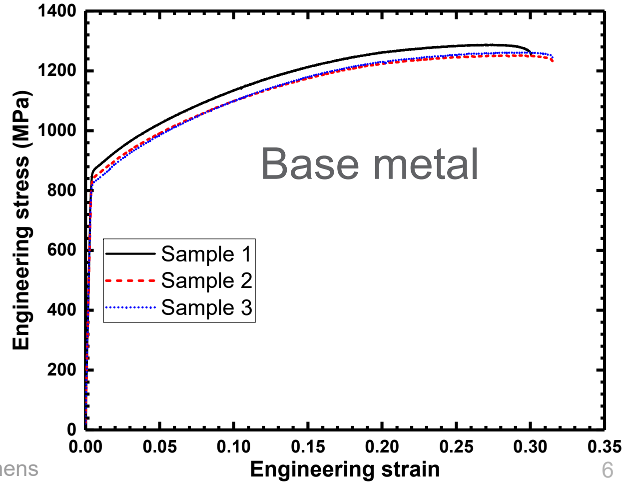
- Step 1:
  - 1010°C(1850°F) / 2 hours / Air Cooled
- Step 2:
  - 788°C(1450°F) / 8 hours / Air Cooled

FSP Region



Room Temperature Tensile Test Coupon



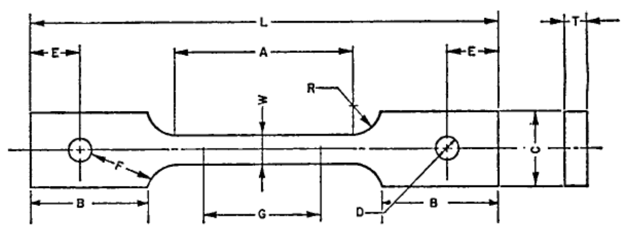


		YS (MPa)	UTS (MPa)	El%
Cross-weld	Sample 1	830	1240	26
	Sample 2	817	1247	26
	Avg.	**824±9**	**1244±5**	**26**
Base metal	Sample 1	869	1287	29.3
	Sample 2	847	1250	31
	Sample 3	833	1261	31
	Avg.	**850±18**	**1266±19**	**30±1**

Propriety Data - Funded Under DOE Project Award #71843 with PNNL Contract PO# 462358 to Siemens

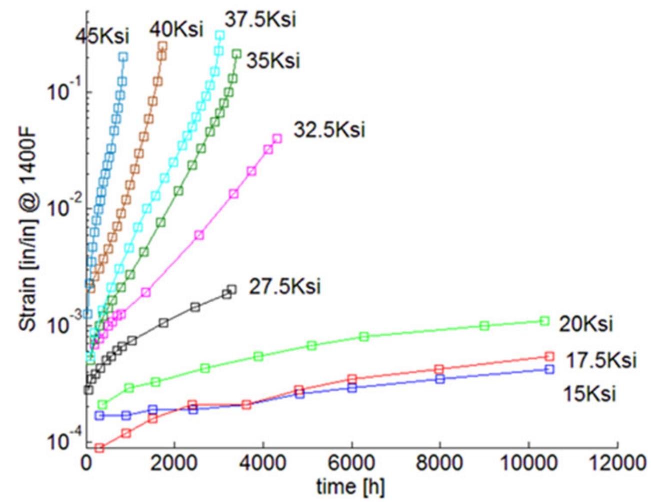
Haynes 282 Properties vs FSP Conditions

- Creep Testing of FSW 282
  - Screening Study: Full Creep Test Study Not Viable with Planned Project Schedule
  - Shorter Term / Higher Stress Levels
    - ✓ 310 MPa (45 ksi)
    - ✓ 190 MPa (27.5 ksi)



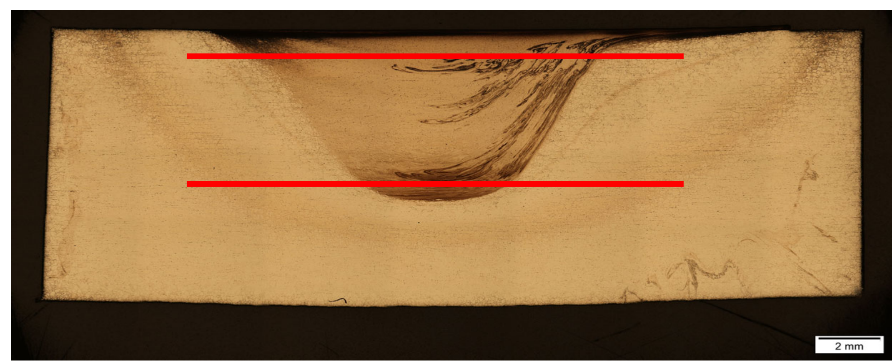
Dimensions, mm [in.]	
G—Gage length	50.0 ± 0.1 [2.000 ± 0.005]
W—Width (Note 1)	12.5 ± 0.2 [0.500 ± 0.010]
T—Thickness, max (Note 2)	16 [0.625]
R—Radius of fillet, min (Note 3)	13 [0.5]
L—Overall length, min	200 [8]
A—Length of reduced section, min	57 [2.25]
B—Length of grip section, min	50 [2]
C—Width of grip section, approximate	50 [2]
D—Diameter of hole for pin, min (Note 4)	13 [0.5]
E—Edge distance from pin, approximate	40 [1.5]
F—Distance from hole to fillet, min	13 [0.5]

Creep Testing Coupon Geometry



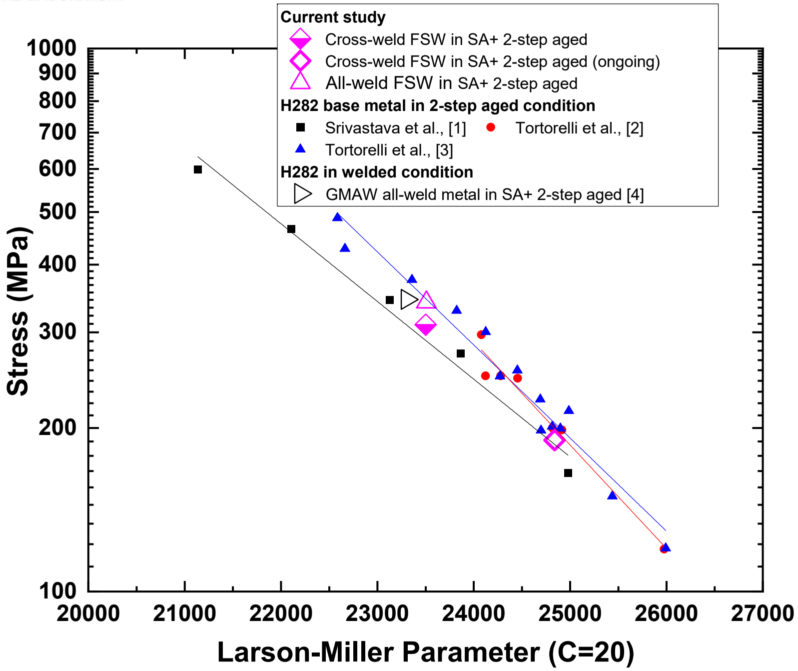
Creep Data for Haynes 282 Base Material*

* C. Shen, Modeling Creep-Fatigue-Environment Interactions in Steam Turbine Rotor Materials for Advanced Ultra-Supercritical Coal Power Plants: Final Report, DOE/NETL Cooperative Agreement DE-FE0005859, April 2014



Creep Testing Coupon Material Area

Hayes 282 Properties vs FSP Conditions



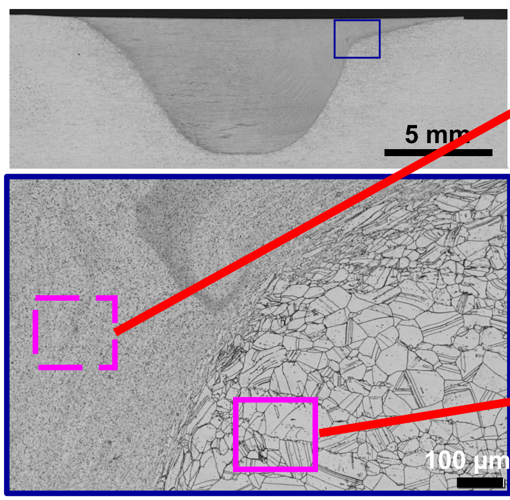
Larson-Miller Chart

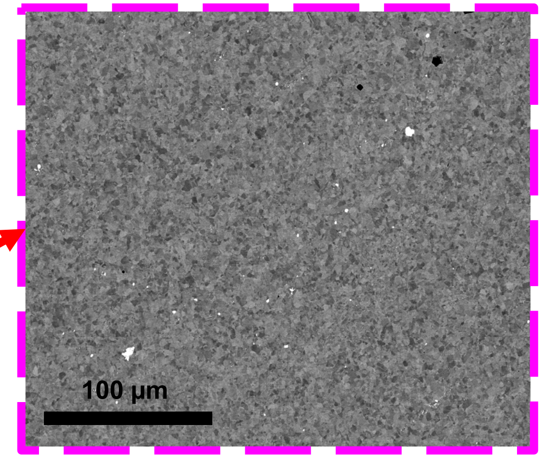
- FSP
  - Processing temperature: 850°C
- Post FSP Heat Treatment:
  - Solution annealing +
  - Two-step aging heat treatment
- Creep test conditions:
  - 760°C and 310 MPa (Completed)
  - 760°C and 190 MPa (Completed)
    - All the cross-weld FSP samples performed similar to the base material.

1. S. Srivastava, J. Caron, L. Pike, Recent developments in the characteristics of HAYNES 282 alloy for use in A-USC applications, in: Proceedings From the 7th International Conference on Advances in Materials Technology for Fossil Power Plants October 22–25, 2013, pp. 120–130
2. P. Tortorelli, K. Unocic, H. Wang, M. Santella, J. Shingledecker, Ni-based alloys for advanced Ultrasupercritical steam boilers, in: Fossil Energy Crosscutting Research Program Review, April 25, 2015, Pittsburgh, Pennsylvania, 2015.
3. P. Tortorelli, K. Unocic, H. Wang, M. Santella, J. Shingledecker, V. Cedro, III, Long-term creep-rupture behavior of Inconel® 740 AND Haynes® 282, Proceedings of the ASME Symposium on Elevated Temperature Application of Materials for Fossil, Nuclear, and Petrochemical Industries March 25-27, 2014.
4. Haynes 282, Haynes international

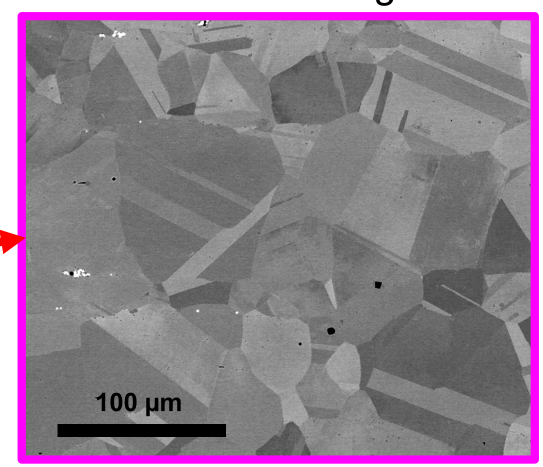
Inconel 617 Properties vs. FSP Conditions

- Cross-Section Transverse to Processing Direction
  - Friction Stir Processed at 850°C shows defect free FSP zone
  - FSP at 825°C showed evidence of small defect
  - Bead-on-plate welds recently made at higher temperature 875°C
  - Significant microstructural refined noted in processed region





Processed region

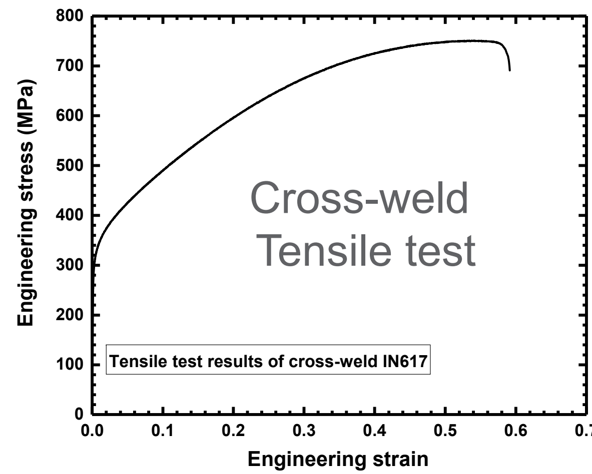


Base material

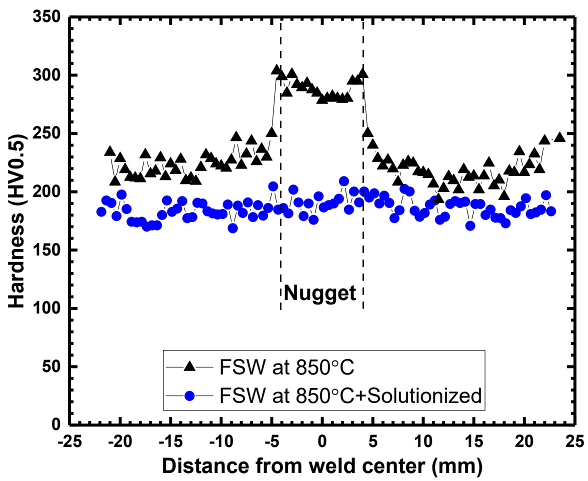
Inconel 617 Properties vs. FSP Conditions

- Cross-Weld Tensile Test
  - After Solution Anneal Heat Treatment
  - Performed at Room Temperature
  - Test parallel to rolling direction
  - Plastic deformation initiated in base metal
  - Failure in base metal
  - Nugget deformation also present

1177°C±15°C for a minimum of 30 minutes followed by rapid quench to 538°C within using inert gas.



FSW has similar yield and ultimate strength compared to base material



Specimen	Yield Strength (ksi) (MPa)	Tensile Strength (ksi) (MPa)
1	44.5 (307)	108.9 (751)
2	45.8 (316)	108.6 (749)

Base metal data (from Special Metals)

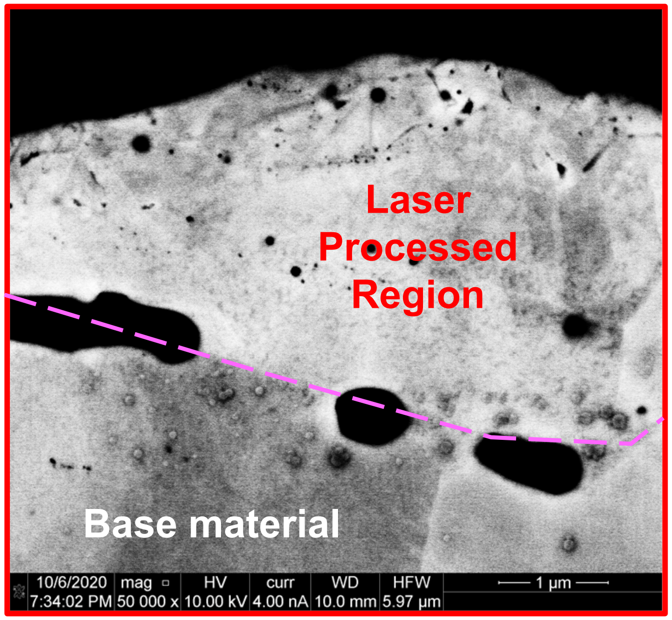
Product Form	Production Method	Yield Strength (0.2% Offset)		Tensile Strength		Elongation, %	Reduction of Area, %
		ksi	MPa	ksi	MPa		
Plate	Hot Rolling	46.7	322	106.5	734	62	56
Bar	Hot Rolling	46.1	318	111.5	769	56	50

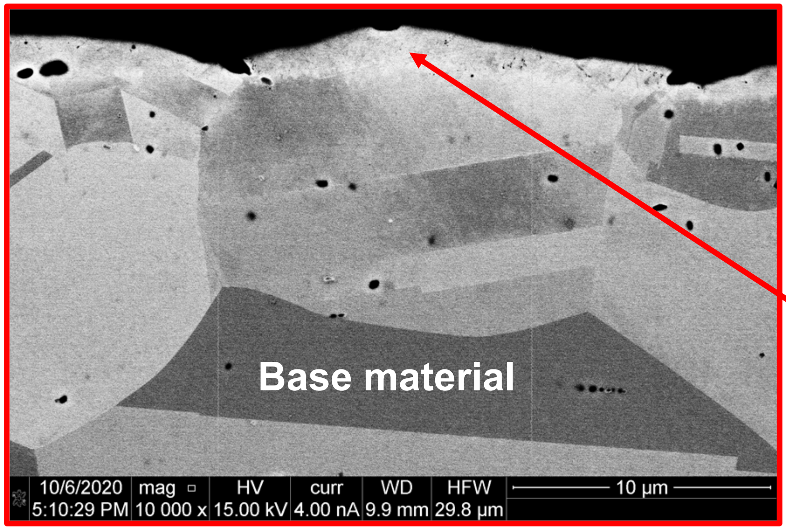
Inconel 617 Properties – Creep testing

- FSP
  - Processing temperature: 850°C
- Post FSP Heat Treatment:
  - Solution annealing (hold 1177°C for 30 mins followed by rapid quenching to 538°C within 15 mins using inert gas)
- Creep test conditions:
  - 760°C and 138 MPa (Ongoing)

Ablation via Laser Processing: Microscopy

- Summary
  - Depth of affected region ~0.5 to 3.3 µm
  - Evidence of melting
  - Cracking not observed
  - Dark particles along boundary with base material
  - Some porosity observed





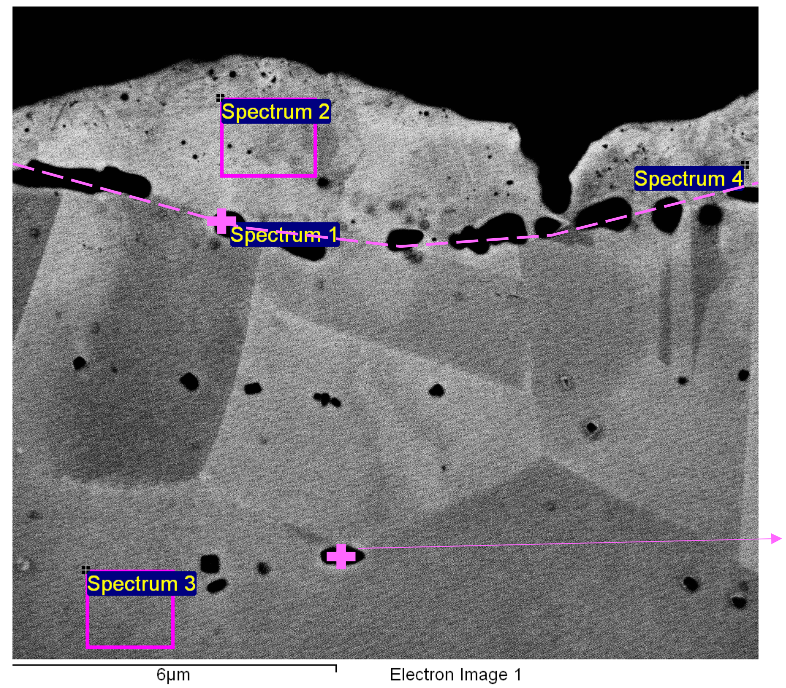
Laser processed region

Laser Ablation Compositional Analysis

- Analysis Summary
  - In LA processed region, Al, Ti and Cr fraction reduce while Fe and Mo fraction increased
  - Dark particles in boundary are rich in Al and O
    - ✓ Aluminum oxide
  - Dark particles in base material are rich in Mo and Ti
    - ✓ Ti and Mo carbides

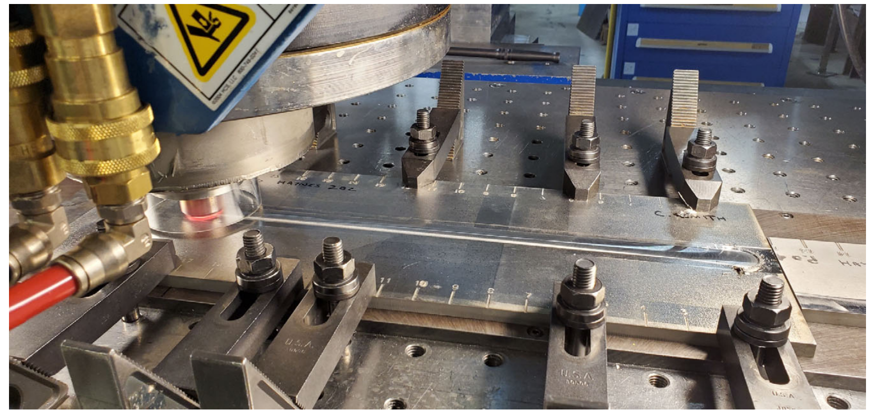
Spectrum	O	Al (↓)	Ti (↓)	Cr (↓)	Fe (↑)	Co	Ni	Mo (↑)	Total
Matrix (Spectrum 3)	0.26	1.13	1.27	15.70	0.76	10.25	62.33	8.29	100.00
Laser processed region (Spectrum 2)	0.36	0.33	0.58	10.80	2.12	11.06	63.54	11.20	100.00
Laser processed region (Spectrum 4)	0.37	0.22	0.60	10.73	2.86	10.60	63.92	10.70	100.00
Dark particles at the boundary (Spectrum 1)	43.00	38.25	0.81	4.22	0.00	1.48	6.52	5.72	100.00
Dark particles in the matrix	0.62	0.77	16.76	14.47	0.63	7.79	43.96	15.00	100.00

Chemical Composition in weight %

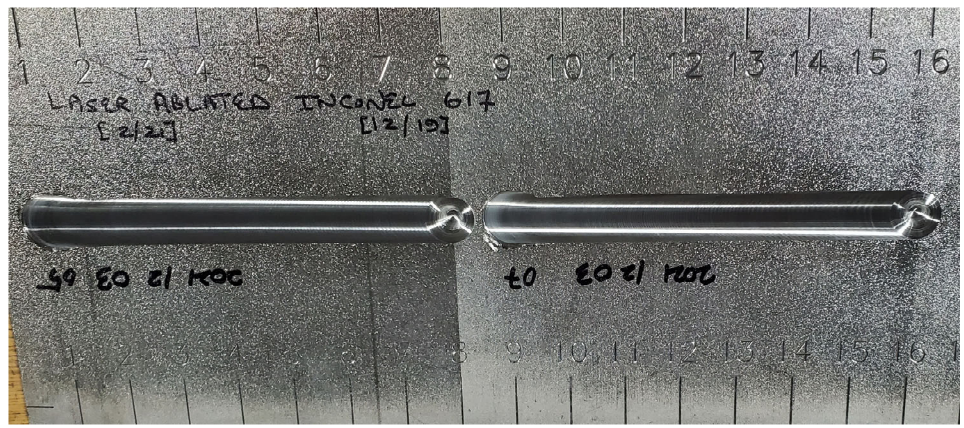


Laser Ablation: Post Friction Stir Processing

- Friction Stir Processing of Laser Ablated Material
  - Can FSP eliminate cast microstructure at surface?
  - Can FSP disperse the agglomerated aluminum oxides near the surface
- Performed FSP at parameters developed from initial process development efforts
- Visual results and other FSP outputs consistent with process development efforts
- Microscopy efforts in progress



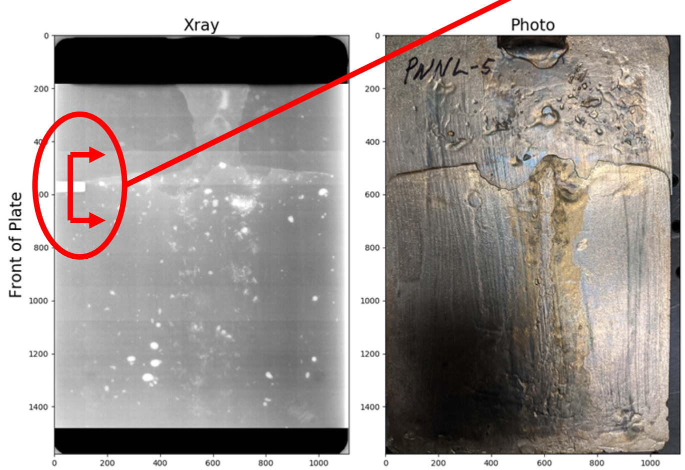
FSP of Laser Ablated Material in Process



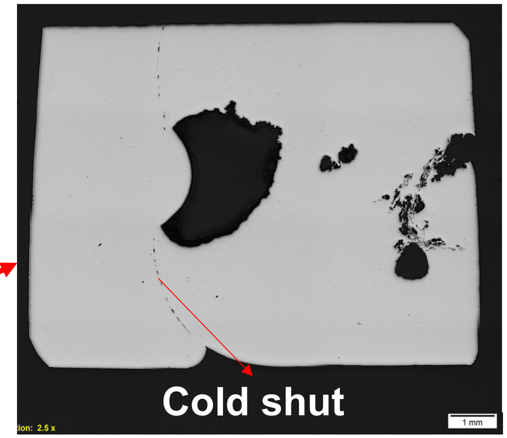
FSP Laser Ablated Plates

Haynes 282 Casting FSP

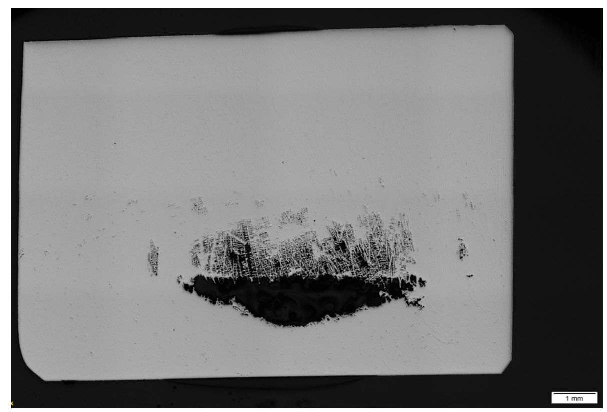
- Objective:
  - Can FSP heal casting indications or defects?
    - ✓ Porosity
    - ✓ Cold shuts



Example Radiographic Image and Locations for Metallography



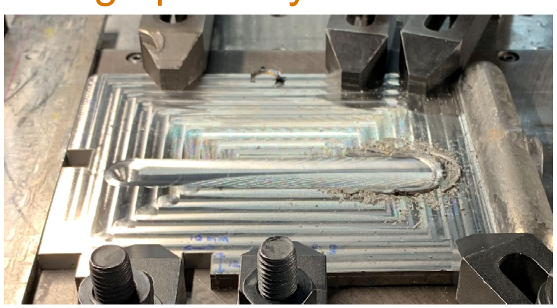
Cast Plate Microstructure in Area of Cold Shut



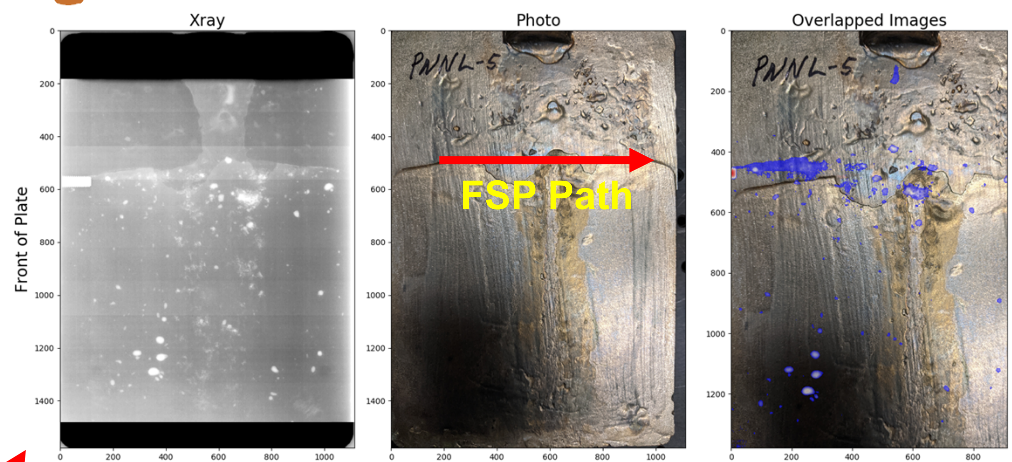
Cast Plate Microstructure in Area of Porosity

Haynes 282 Casting FSP

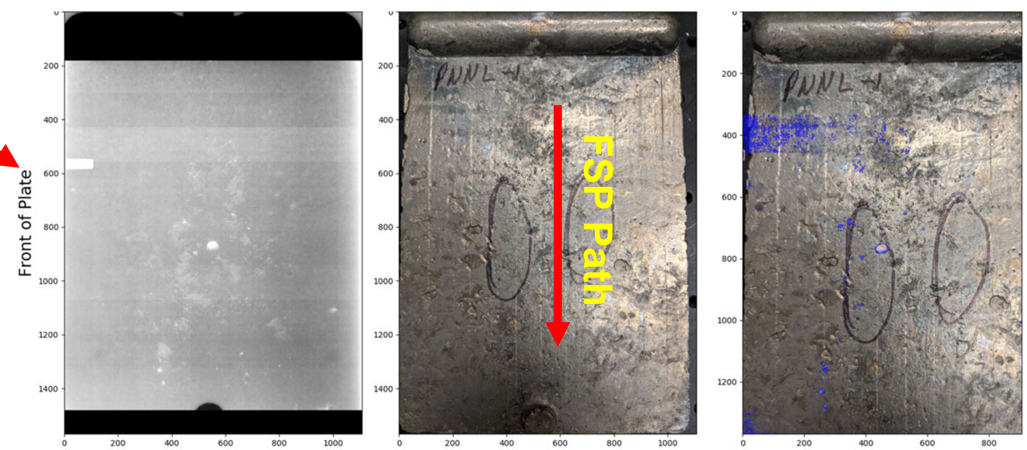
- Castings Fabricated
  - Intentionally tried to make defects
- Pre-FSP Analysis Completed
  - Radiography
  - Metallography
  - FSP paths planned
- Initial FSP Completed
  - Along cold shut
  - Through porosity



FSP Thru Porosity

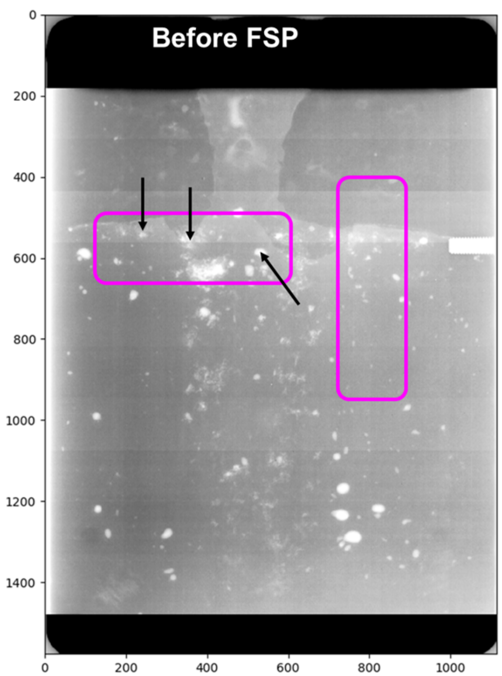


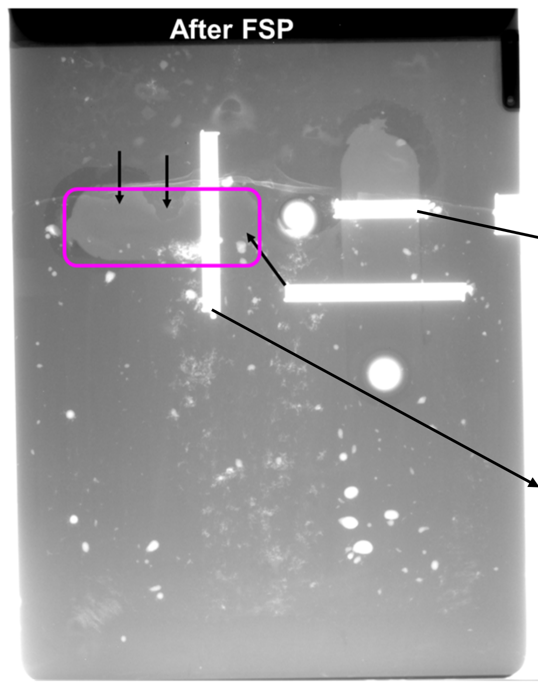
Radiography **As Cast Plate** **Overlayed Images**

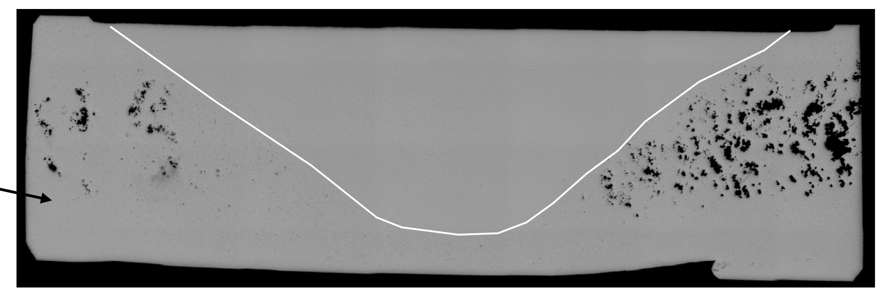


Haynes 282 Casting FSP

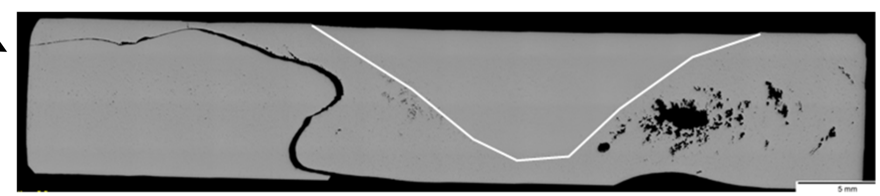
- Post FSP Radiography and Metallography
  - Indicates FSP can heal porosity and cold shut lack of bonding







FSP Stirzone in region of porosity



FSP Stirzone in Region of Cold Shut

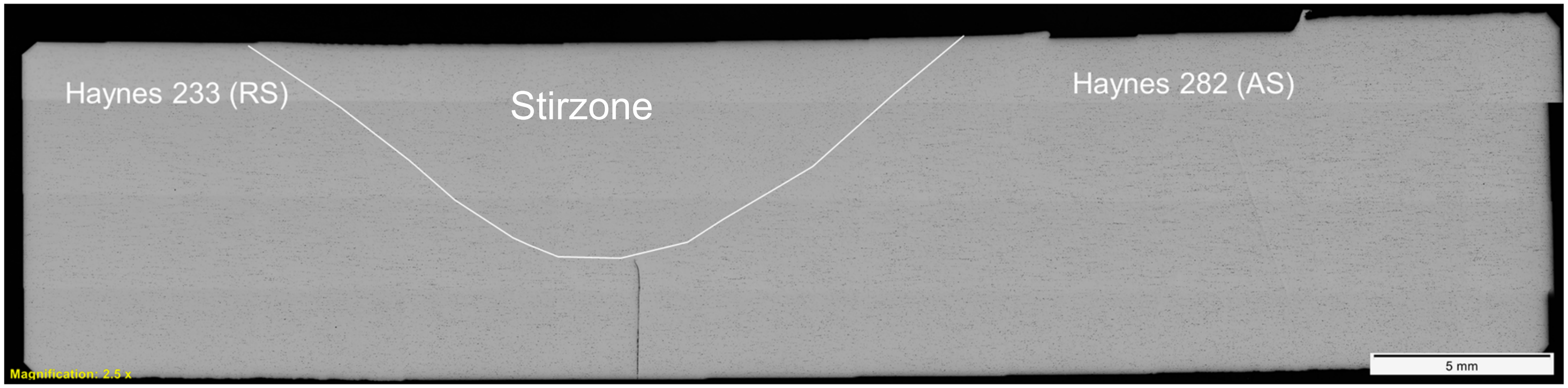
Dissimilar Material Weld: Haynes 282 to 233

- Objective: Assess capability to create dissimilar material joint
  - Can enable custom alloy selection for products with varying requirements based on location
- Friction Stir Weld joints created at parameters used for Haynes 282
- Visual results similar to Haynes 282 trials

Example of FSW of Haynes 282 to Haynes 233

Dissimilar Material Weld: Haynes 282 to 233

- Microscopy
  - Haynes 282 was placed on the advancing side and 233 was placed on the retreating side (RS) due to 282 exhibiting higher strength compared to 233 at the processing temperatures

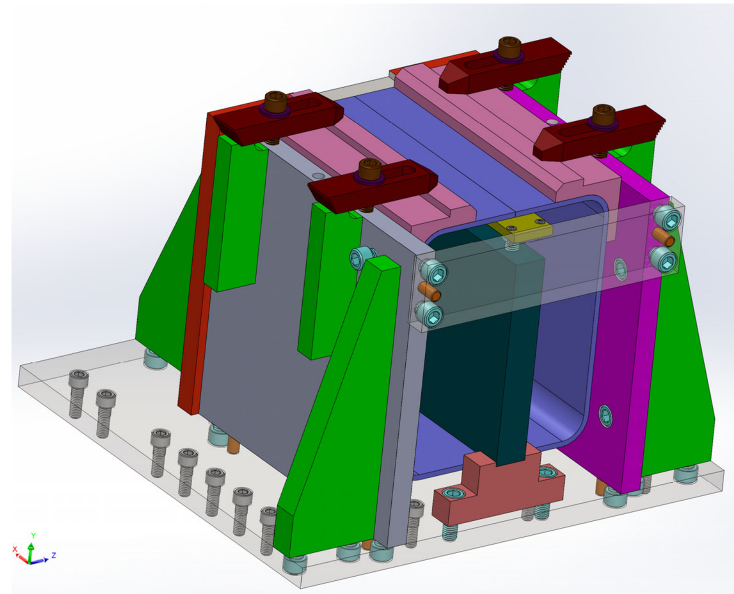


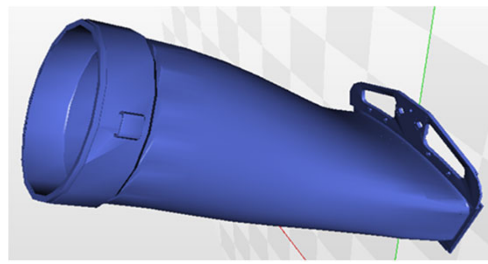
Microstructure of Haynes 282 to Hayes 233 Friction Stir Butt Weld

  - Advancing Side: Side of weld where travel direction and FS tool velocity is parallel
  - Retreating Side: Side of weld where travel direction and FS tool velocity are opposite

Prototypic Part Fabrication

- Objective: Demonstrate FSW of Nickel Super Alloy at Prototypic Part Level

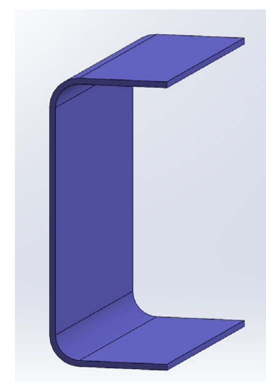




FSW Fixture with Parts to be Welded

Prototypic Assembly Detail Parts

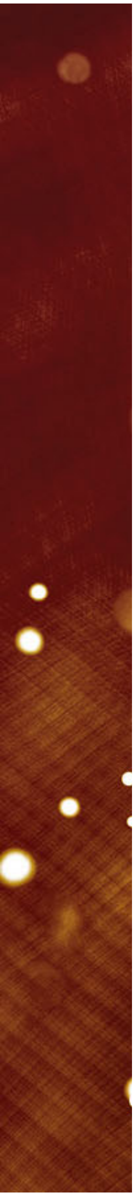
Mimics Transition Duct via Joining of Two C-Channel Sections



Future Tasks

- Complete Welding of Prototypic Parts
- FSP as potential to Improve Diffusion Bonding Process
  - Lower cycle time?
  - Reduce polishing need?
- FSP as potential to improve Thermal Barrier Coating
  - Can FSP enhance adhesion performance?
- Dissimilar Material FSW - Haynes 282 to Haynes 233
  - Mechanical testing
- Analyze fusion weld (plasma arc welding) of Haynes 282 versus FSP
  - Metallography

Acknowledgment: This material is based upon work supported by the Department of Energy Award Number DE-FWP0071843.



Pacific Northwest
NATIONAL LABORATORY

Thank you