Welding and Weldability Concerns for Additively Manufactured Materials

William Evans – NASA MSFC

Eric Brizes – NASA GRC

Antonio Ramirez – The Ohio State University

NASA / Marshall Space Flight Center



Agenda

- **Introductions**
- **Background – DED at NASA**
- **AM Welding Concerns**
- **Weldability Background**
- **Weldability Testing**
  - Varestraint Testing
  - Literature Comparisons
- **Welding Case Study – RAMFIRE**
- **Conclusions**
- **Acknowledgments**
- **References**



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Introduction – William Evans, Welding Engineer







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Welding Concerns for AM

- Additive Manufacturing has introduced a new form of raw material and little research has been conducted to compare weldability responses of AM alloys
  - Most assume there is no difference…
- In theory, most conventional welding processes should be capable of performing a weld on AM material.
  - Most AM processes are derived from welding processes
- Experiences at NASA and literature have shown the following processes to successfully conduct welds on metal AM components
  - Gas Tungsten Arc Welding (GTAW), Laser Beam Welding (LBW), Electron Beam Welding (EBW), Laser-Arc Hybrid, Resistance Welding, and Friction welding processes
- When welding with filler metals, normal filler metal selection applies
  - However, with new materials designed for AM there are often no matching filler metals.
- One consideration that is important to welding processes are post build heat treat conditions, most AM builds do receive some form of heat treat regime
  - Some research has shown as HIP'd material performs poorly to welding
  - NASA has observed material in the solution heat treated conditions welds better

Use of conventional welding engineering principals apply directly to AM metals. Care should be given to material condition and AM should be treated as a new metal product form.

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Welding Concerns for AM – Cont.

- **Pre-Weld Joint Preparations**
  - "Cleanliness is next to Godliness" especially with AM parts
  - At a minimum remove build remnant surface finish
  - Joint lands should be cleaned the same as conventional welding
- **Weld Inspection Methodology**
  - Weld inspection is paramount in flight hardware
  - Keep post weld inspection in mind, surface finish is important
  - In an ideal world an inspector should be able to differentiate between a build defect and a weld defect. (E.g. porosity in the base metal vs. in the weld metal)

Conventional production welding practices for flight hardware should be maintained when welding AM components.

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Welding Design Considerations for AM Components

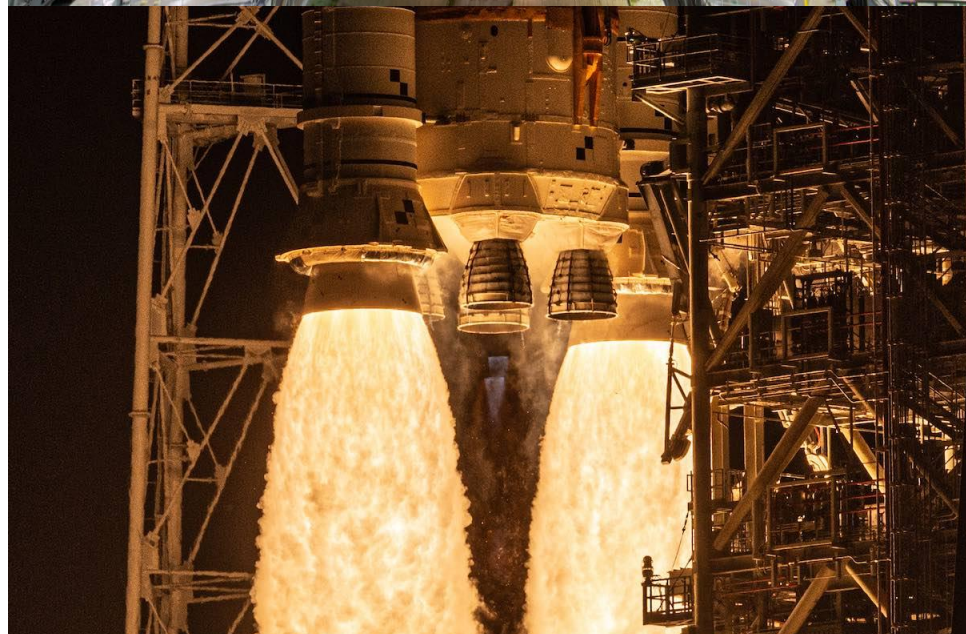
- Weld Joint Design
  - Design parts with weld joint in mind
  - Often a thicker section is required for an adequate weld
  - Enough stock for joint machining
- Weld Joint Inspection
  - Joint area should be clear of build layers for inspection.
  - Do you plan to use an Ultrasonic probe?
  - Can the joint be clearly observed with X-ray?
- Weld Property Knock Down
  - Fusion based welding process will cause a joint efficiency knock down
  - Can conduct a post weld heat treat to recover properties
- Build direction/grain orientation
  - Some welding processes perform better with certain grain orientations
  - This is not always possible to control
  - NASA conducts weld development with final part grain orientation in mind, property variations have been reported and observed on space flight hardware

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Weldability Introduction

- **Weldability -** The capacity of a material to be welded under fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended service. (American Welding Society)
- Weldability testing is conducted to ensure new metals can be introduced to service and be readily welded and fabricated
  - Results vary with chemistry, stock material type (forging, casting, additive manufacturing), and weld joint geometry
- NASA has been investigating new manufacturing techniques (AM) for cost reducing and improving productivity to support the longevity of the Artemis program

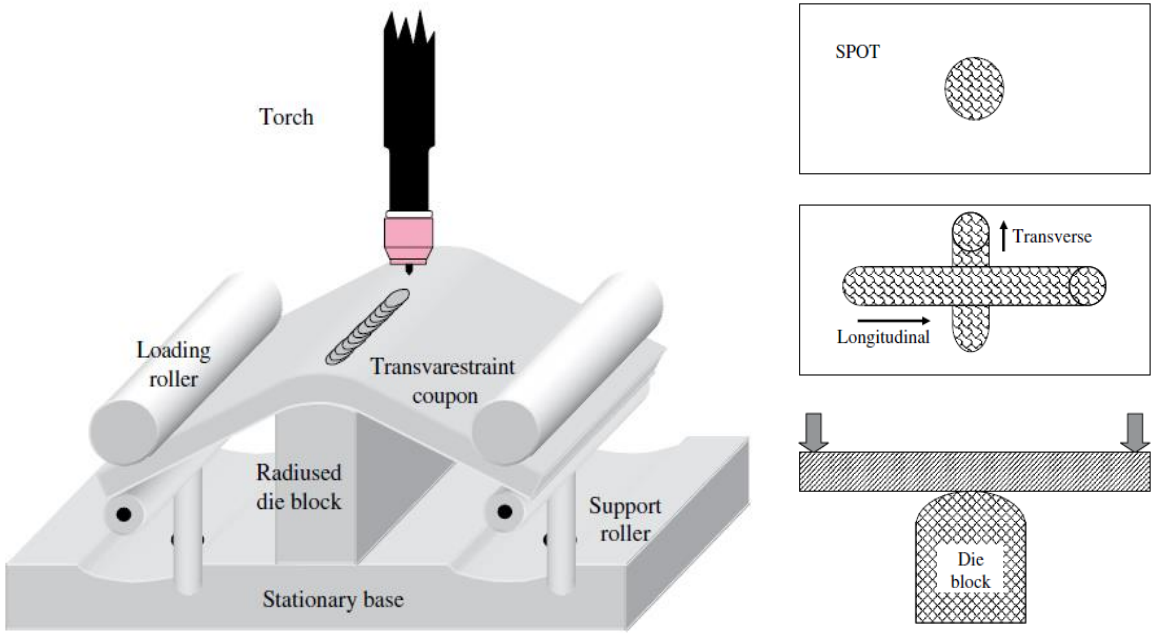


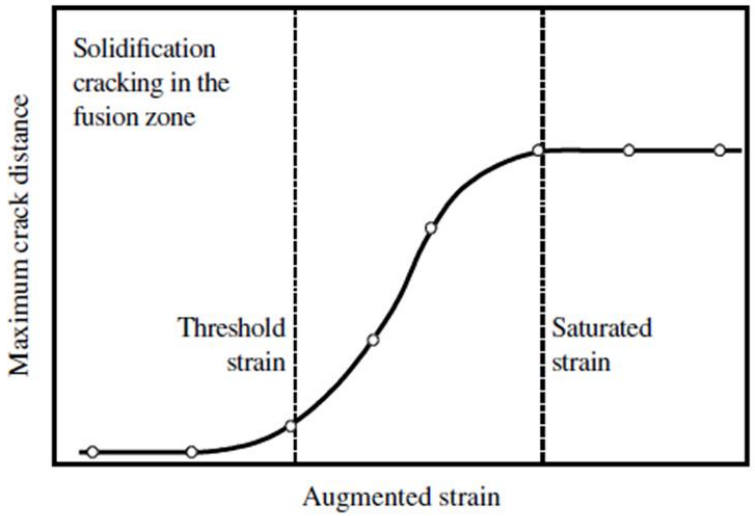


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Introduction – Varestraint Testing

- Developed in 60's as a simple augmented strain test focused on evaluating Hot-cracking susceptibility [1,2]
- A weld puddle is developed using a GTAW torch, strain is applied at the end of solidification, cracks form due to externally induced strains
- Bending occurs rapidly between 2-10 in/s
- Cracks are counted and measured after testing
- Several different measurements can be used for comparison:
  - Total Crack Length
  - Maximum crack distance
  - Number of cracks
- Testing is generally autogenous, but filler metal can be applied using special samples

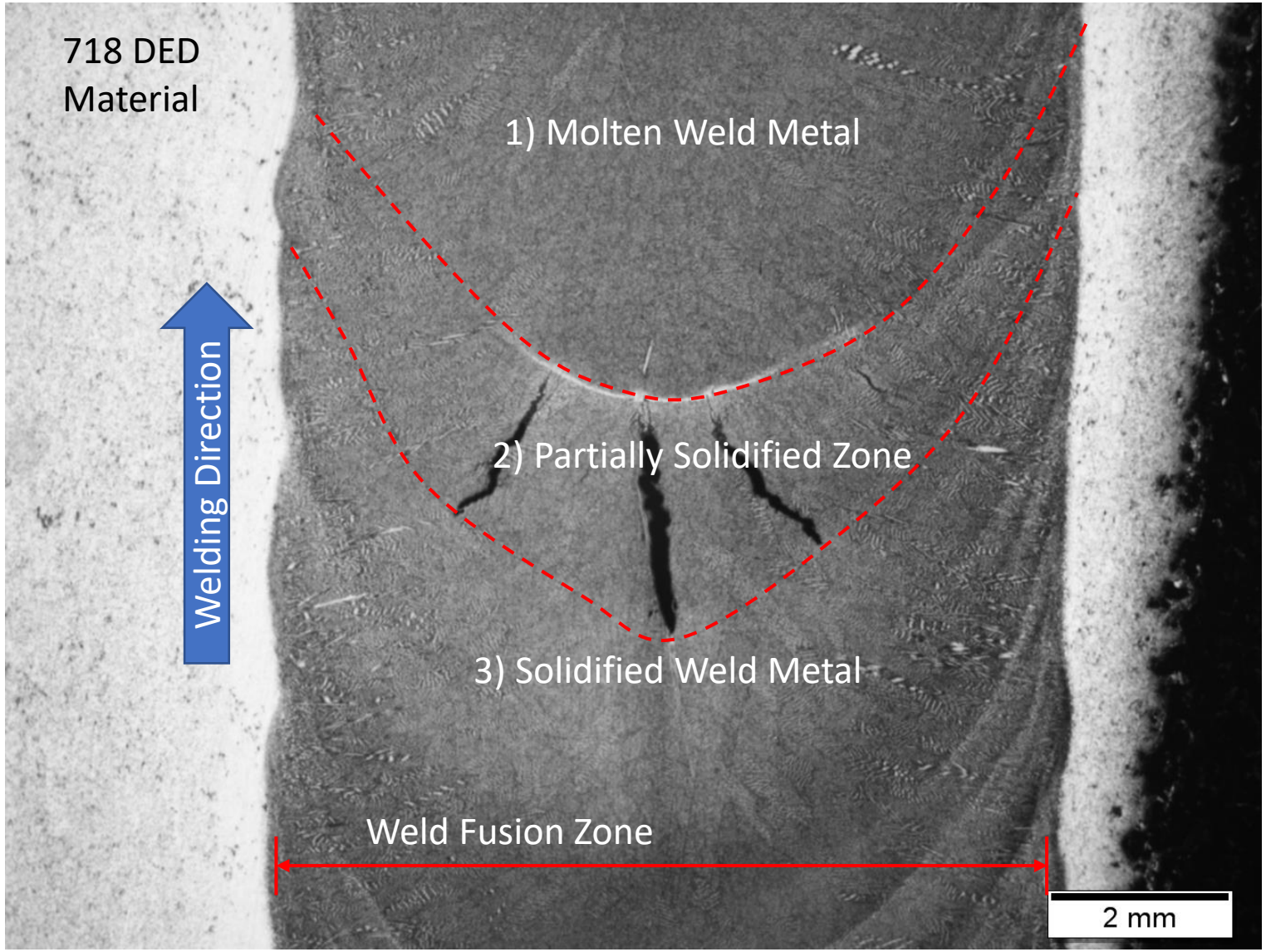




Above: Schematic of Trans-varestraint testing set up
Left: Example plot of maximum cracking distance vs. strain

Regions of a weld during a Varestraint test

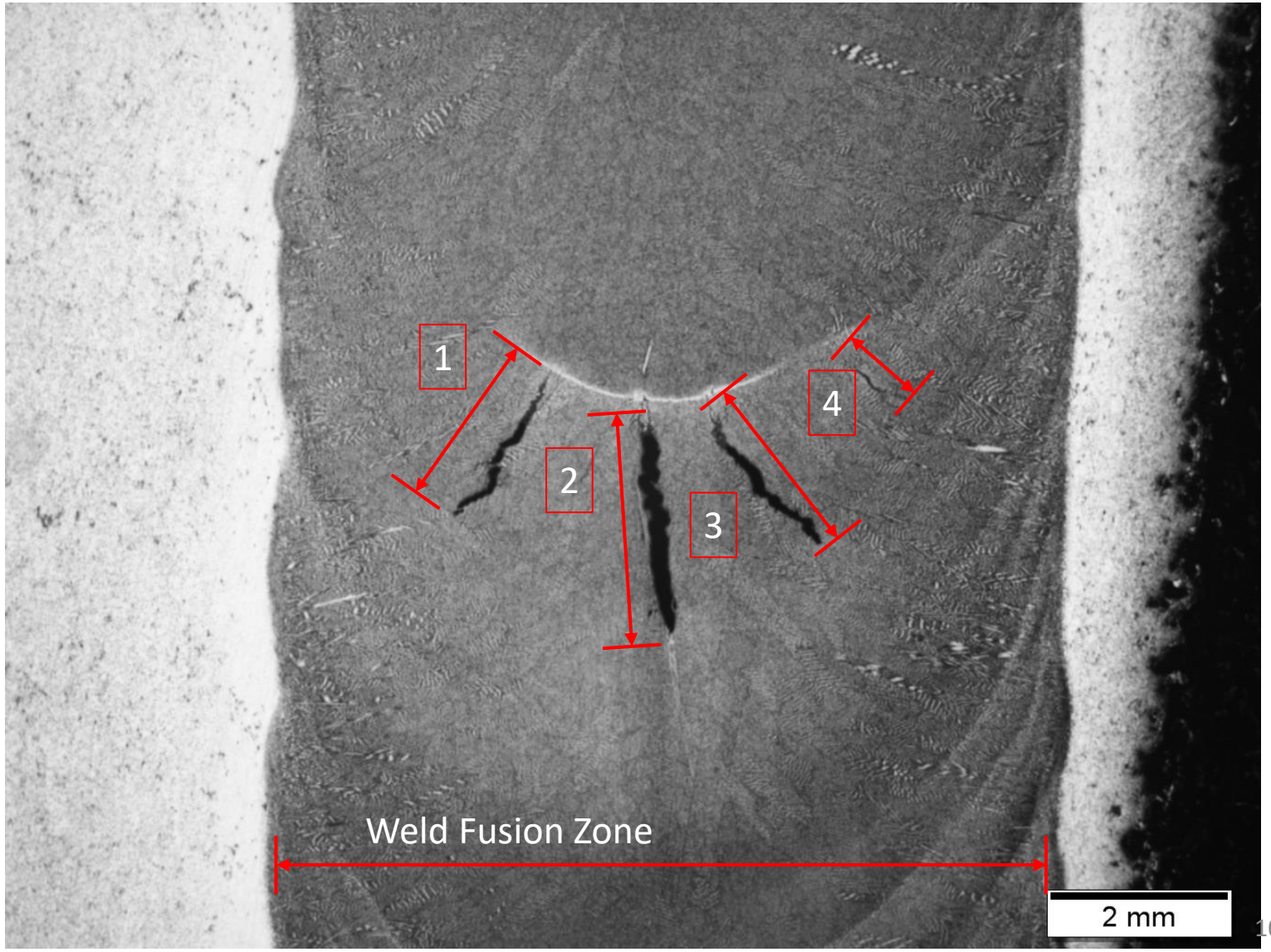
- At the point of bending the specimen there exists 3 major regions in the weld:
- Molten Weld Metal (all liquid)
- Partially Solidified Zone (some liquid)
- Solidified Weld Metal (no liquid)



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Total Crack Length

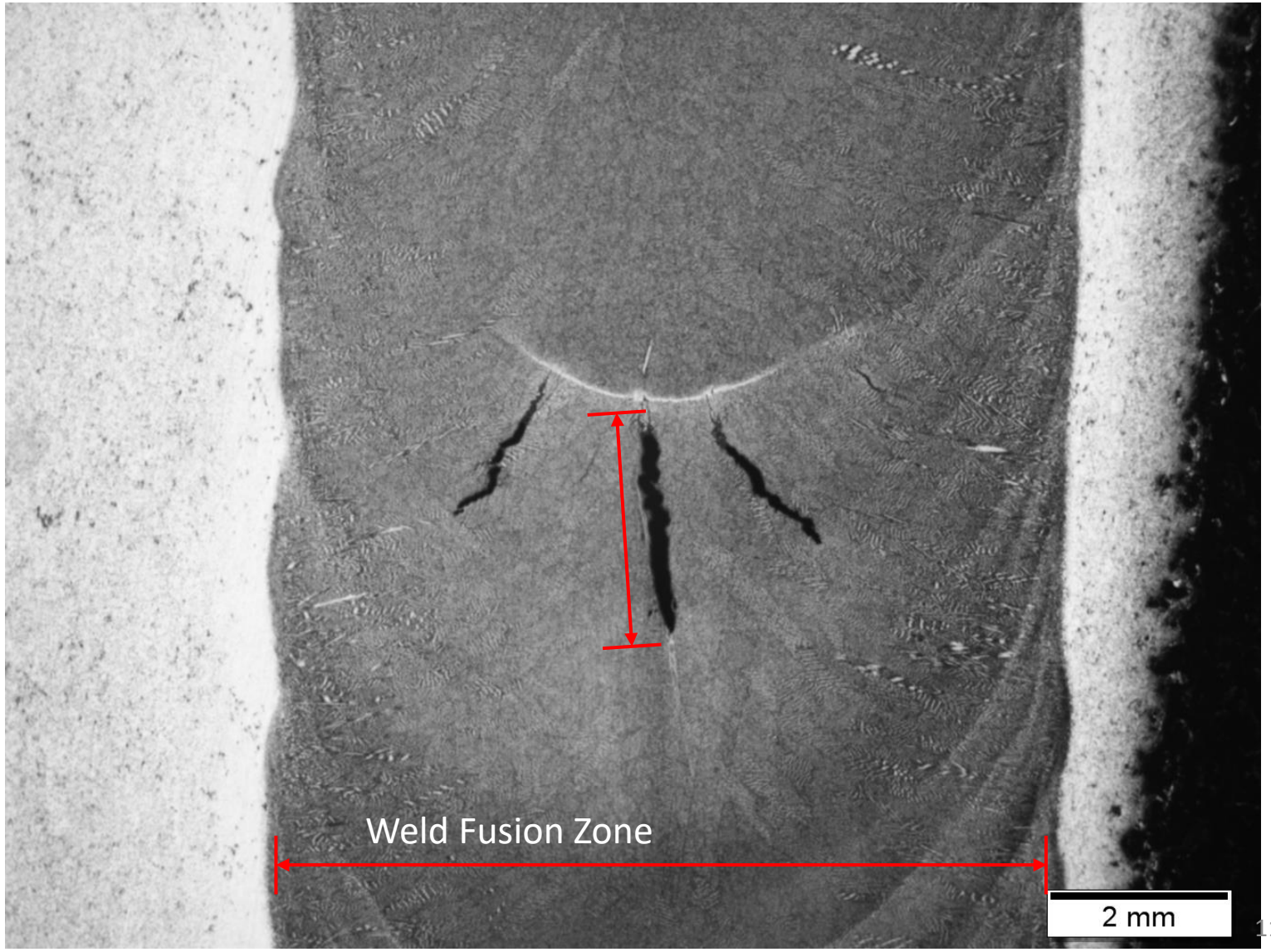
- Summation of the length of each crack
- C1+C2+C3+C4=TCL
- Quantifies number of cracks and the overall severity of the cracks found in the fusion zone
- Can be used as a pseudo tie breaker



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Maximum Crack Distance

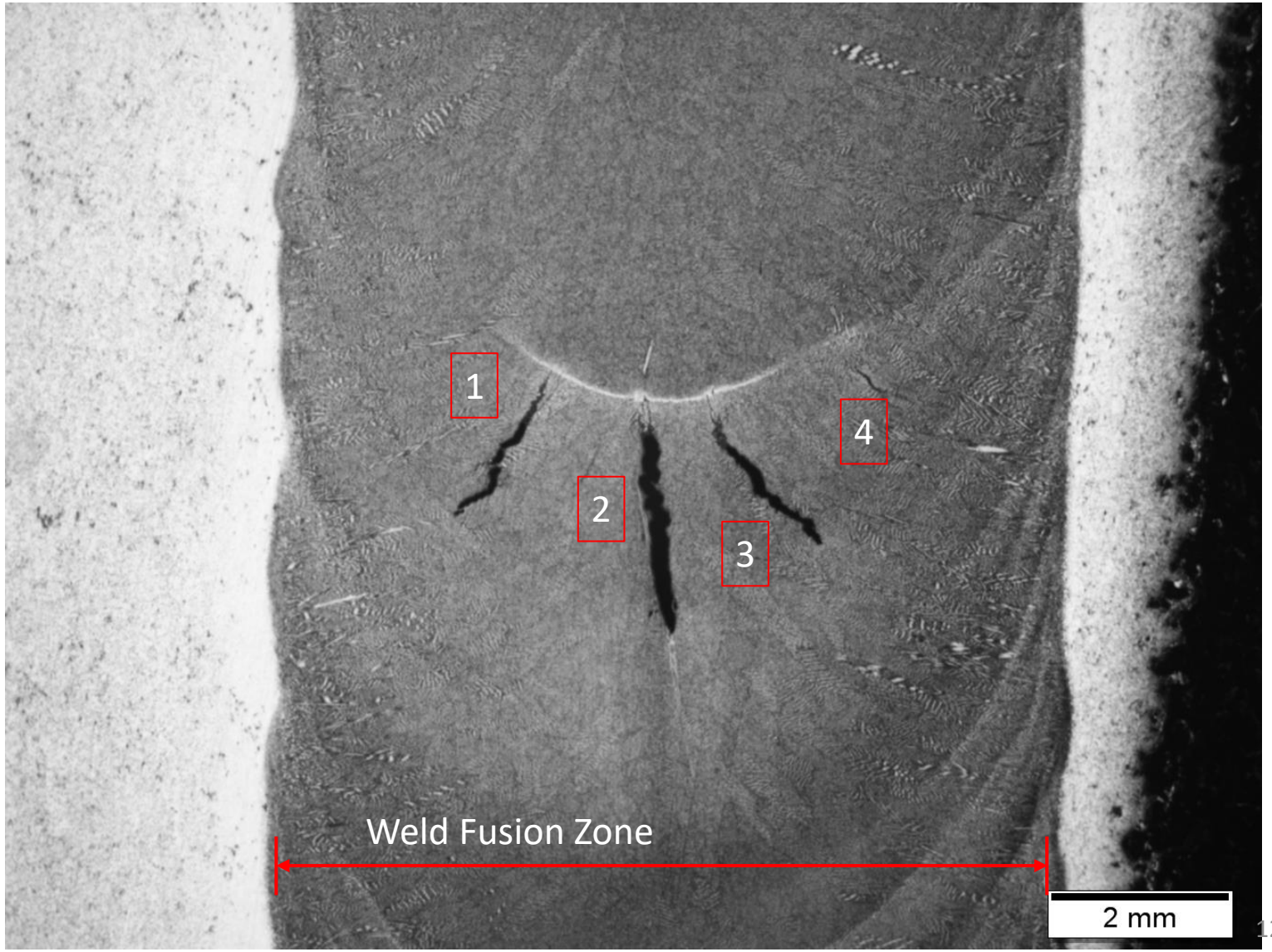
- Length of largest crack observed in weld fusion zone
- Quantifies worst case cracking
- Measuring length in a straight line from crack tip to crack tip
- Commonly reported in literature



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Number of Cracks

- Simply counting the number of cracks
- Not always representative of worst-case cracking
- Many small cracks not always worst alloy

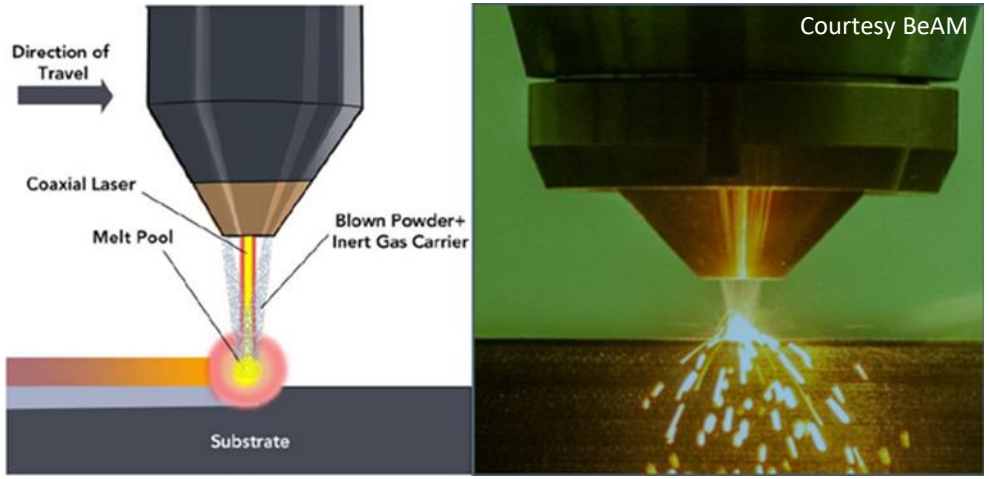


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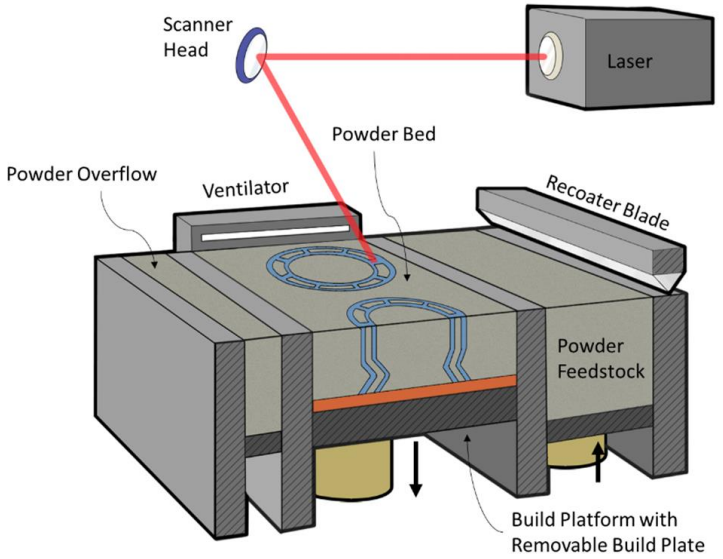
Material Background

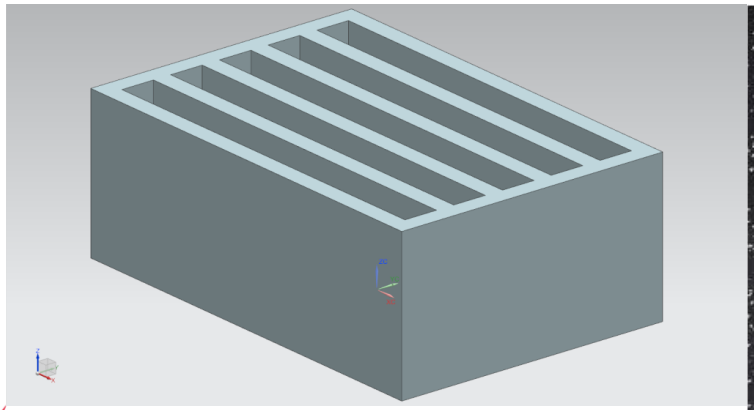
- Two materials investigated
  - Ni 718
  - Ni 625
- Three material manufacturing methods
  - Wrought (rolled plate)
  - Laser Powder Direct Energy Deposition (LP-DED)
  - Laser Powder Bed Fusion (L-PBF)
- All Materials Welded in the solution heat treated condition
- AM material was stress relieved and homogenized

LP – DED Process

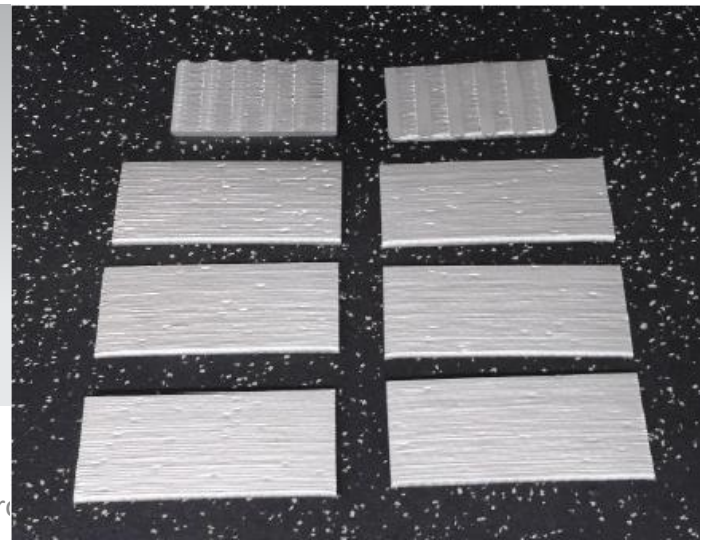


L-PBF Process





Courtesy RPM Innovations

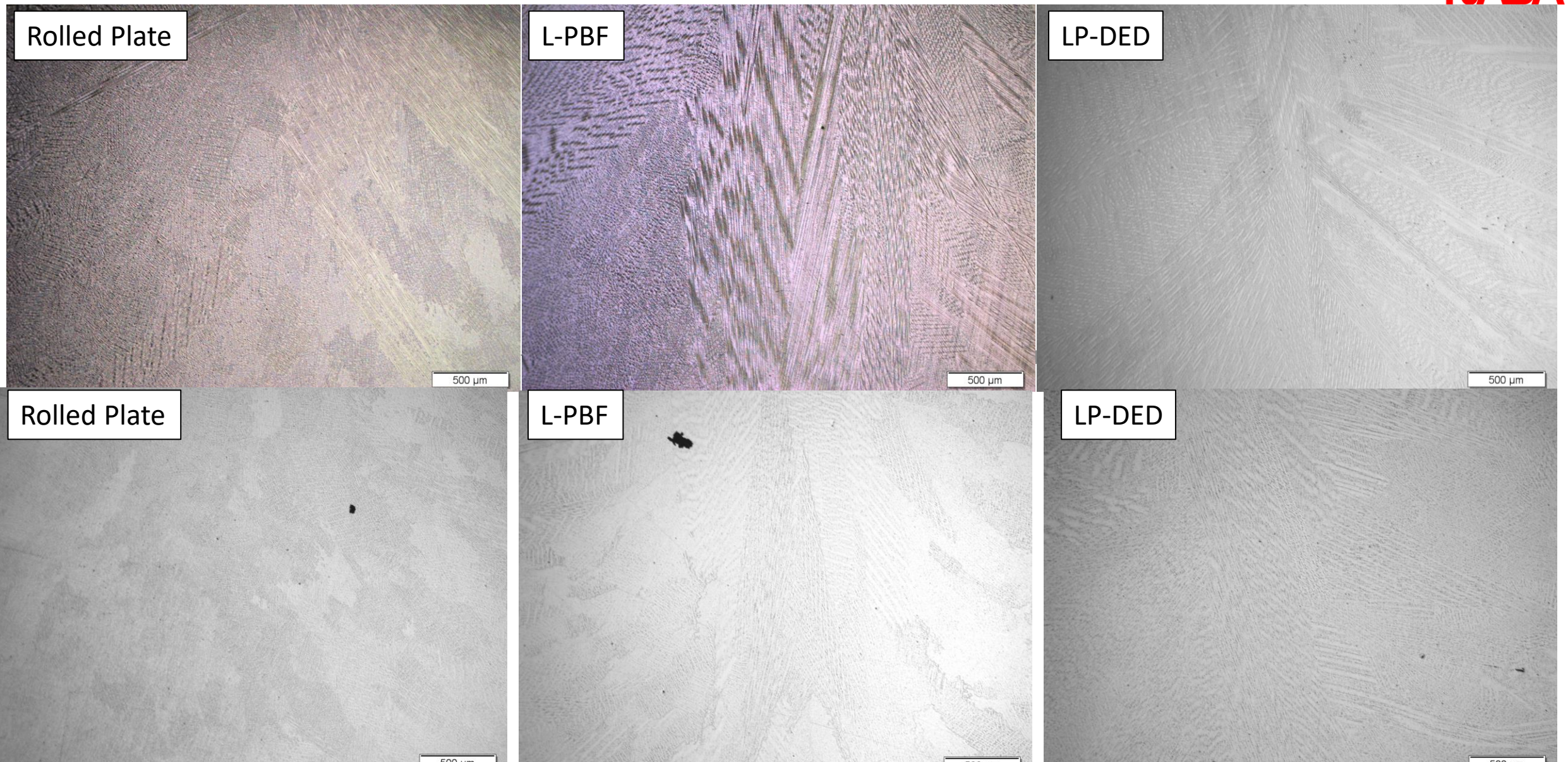


Material Chemistry

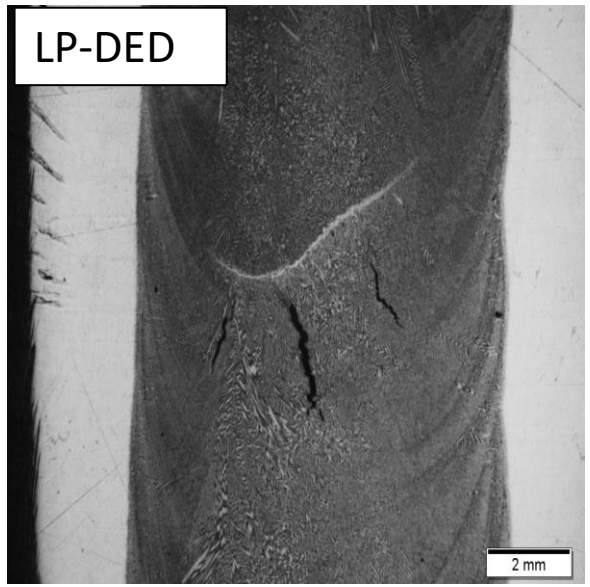
Element	Alloy 625			Alloy 718		
	Wrought	L-DED	L-PBF	Wrought	L-DED	L-PBF
Ni	60.7	61.8	62.3	54.1	53.1	54.8
Cr	22.0	21.5	21.7	18.5	19.2	19.2
Fe	4.39	3.83	4.37	17.33	18.23	17.48
Mo	8.40	8.68	8.18	2.93	2.96	3.06
Co	0.09	0.02	0.06	0.28	0.03	0.04
W	0.03	0.01	0.03	0.02	0.01	0.03
Nb	3.32	3.43	2.76	4.89	4.88	3.67
Ti	0.20	0.16	0.07	1.01	0.90	0.82
Al	0.10	0.10	0.12	0.46	0.53	0.46
Si	0.16	0.13	0.17	0.10	0.06	0.13
Mn	0.43	0.16	0.07	0.12	0.04	0.04
C	0.063	0.027	0.054	0.037	0.046	0.080
N (ppm)	209.9	170.0	69.1	74.3	87.9	85.6
O (ppm)	6.6	50.8	206.8	4.8	33.8	176.1

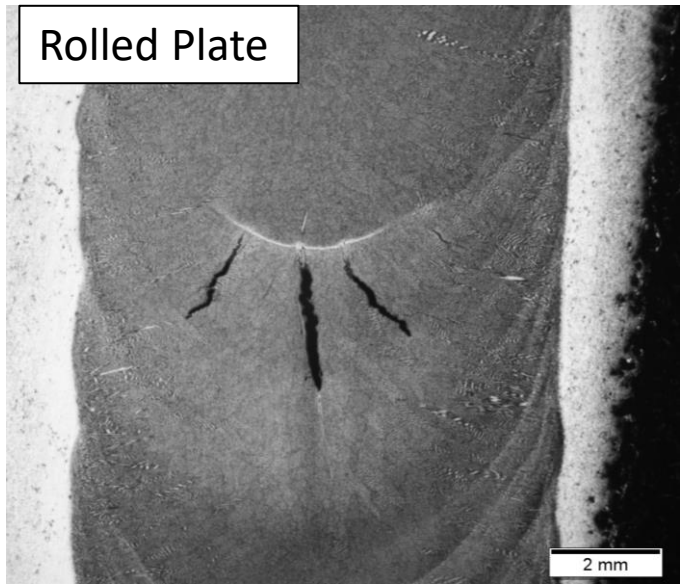
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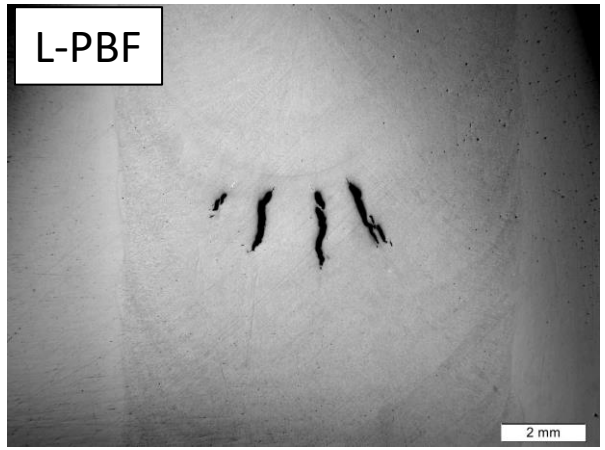
Base Material Metallography – Ni 625

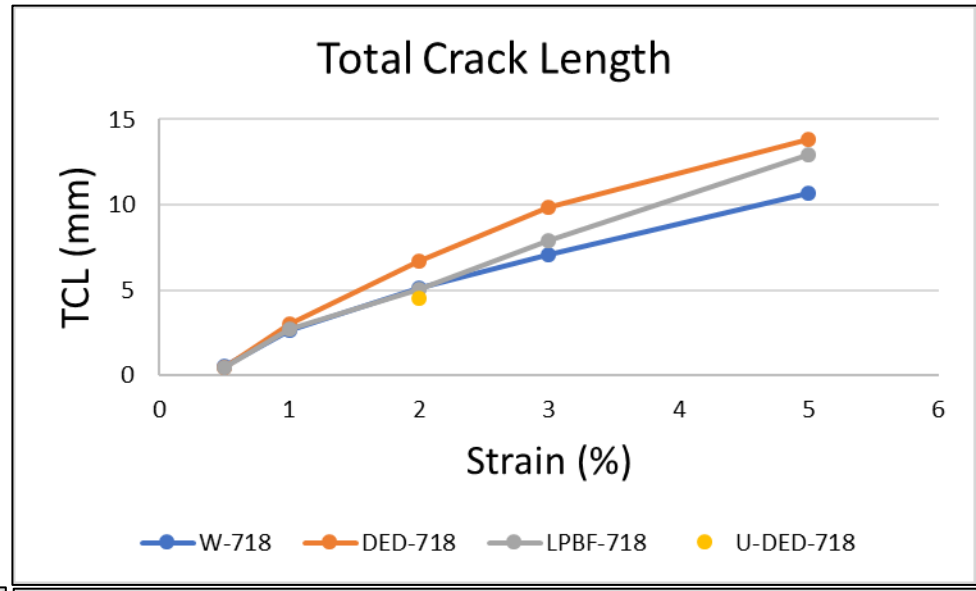


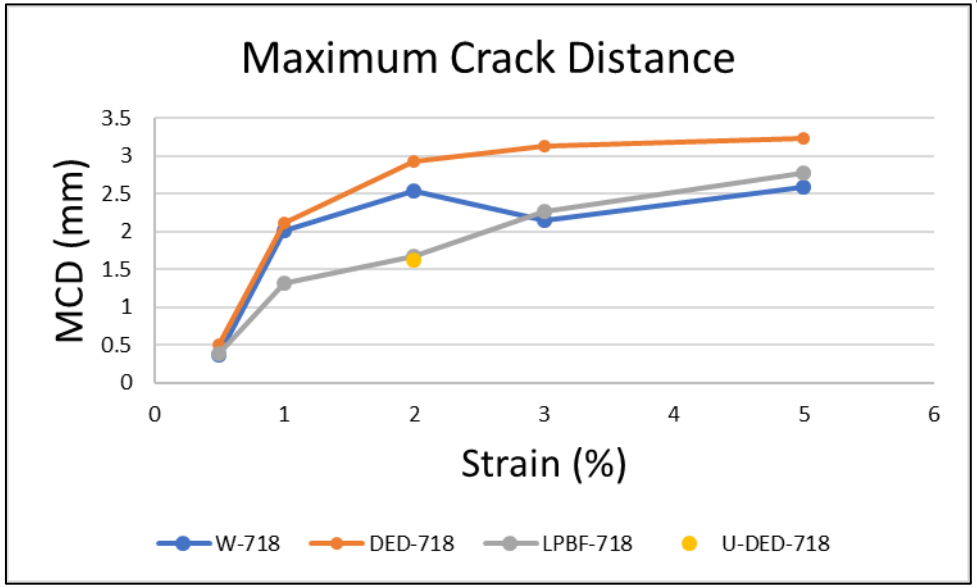
Ni – 718 Transverse Varestraint Results

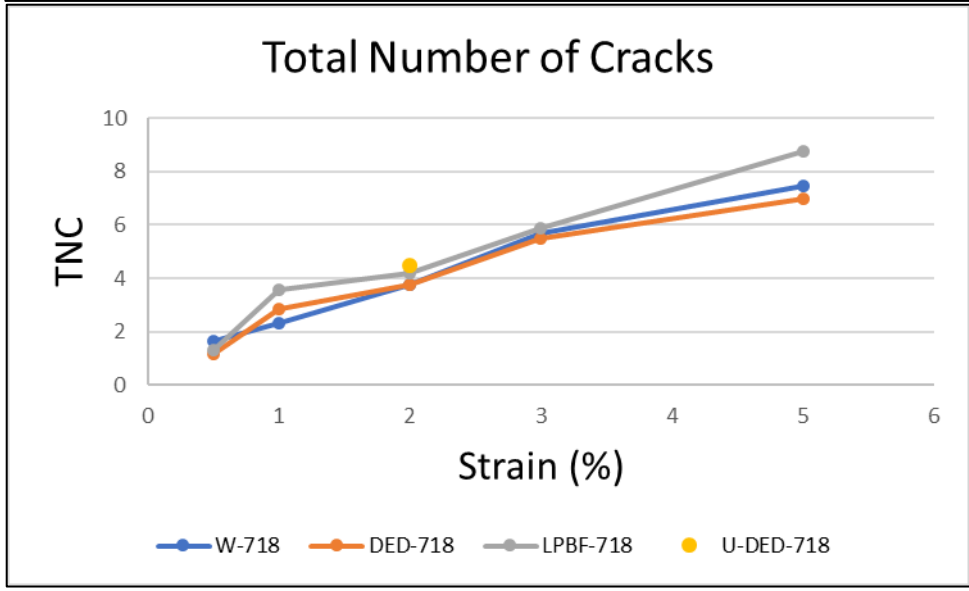






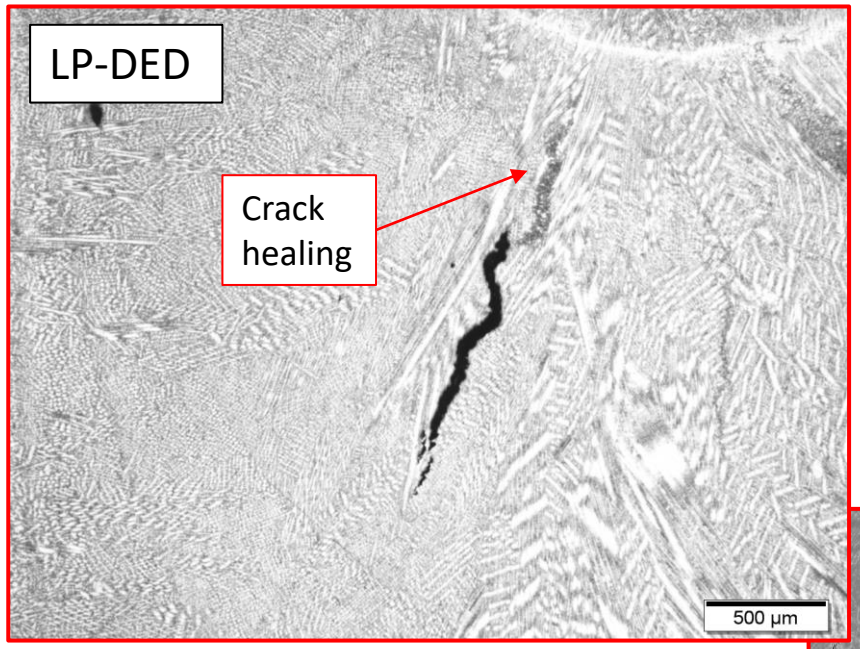


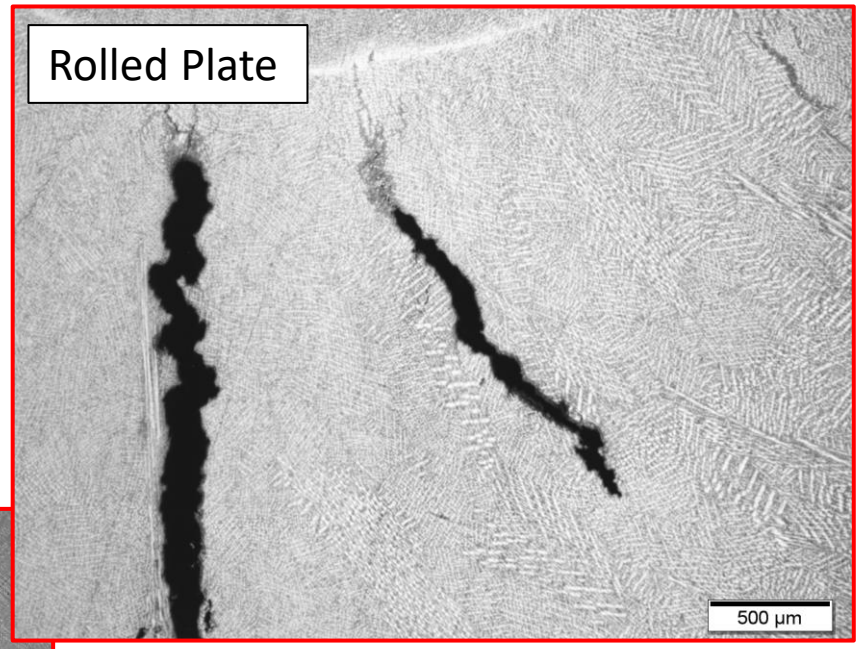


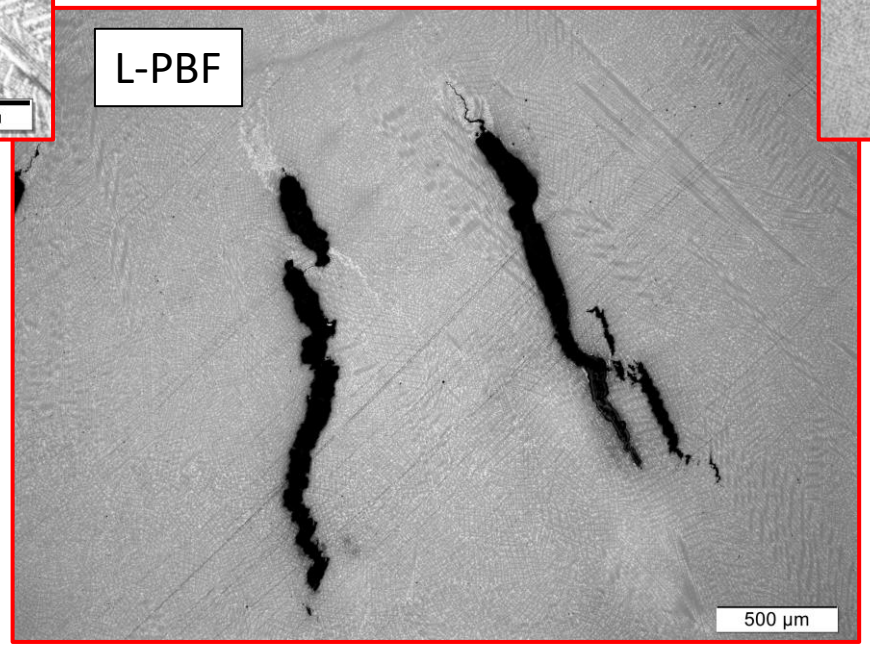


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Ni – 718 Transverse Varestraint Results

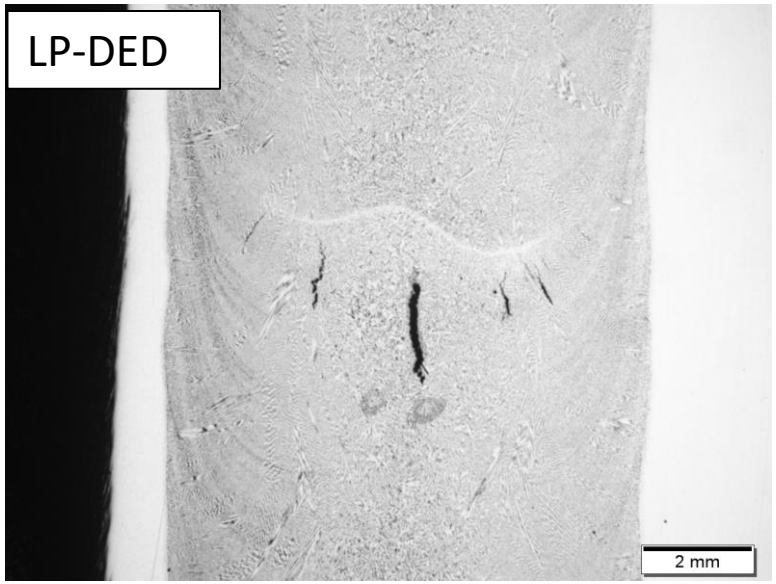


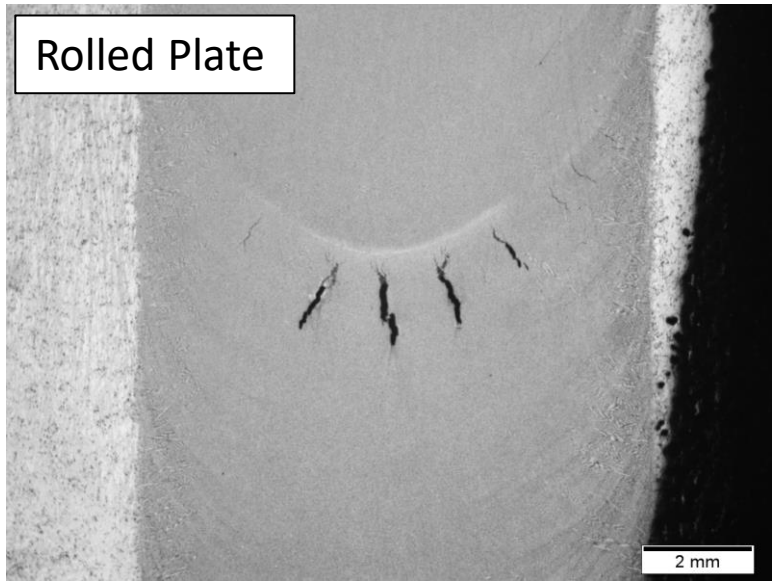


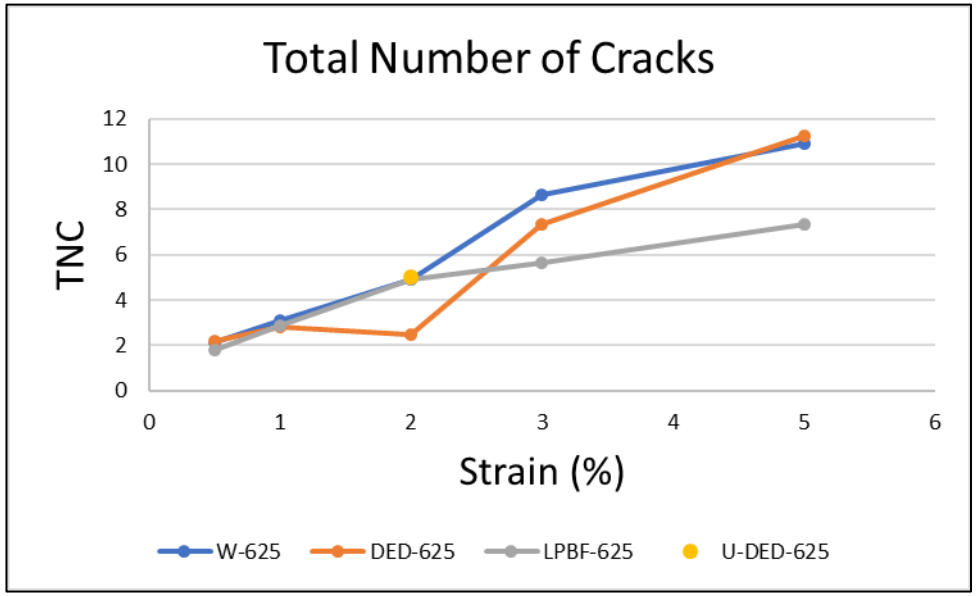


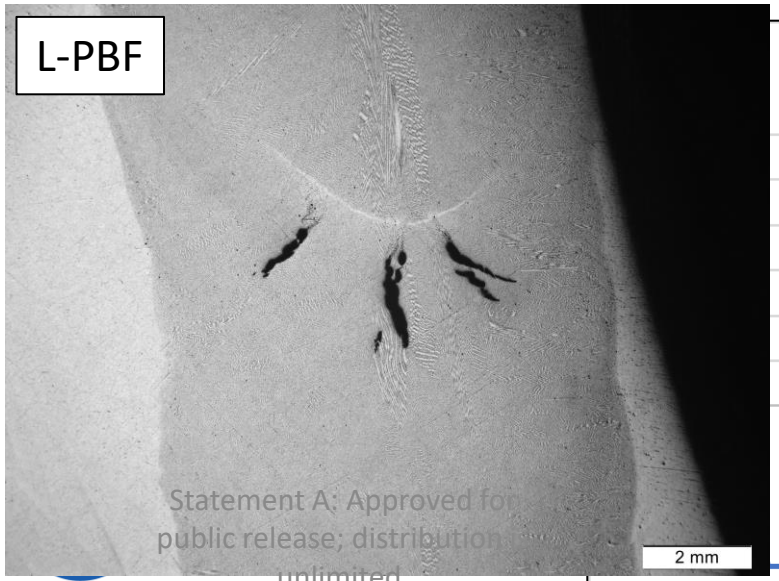
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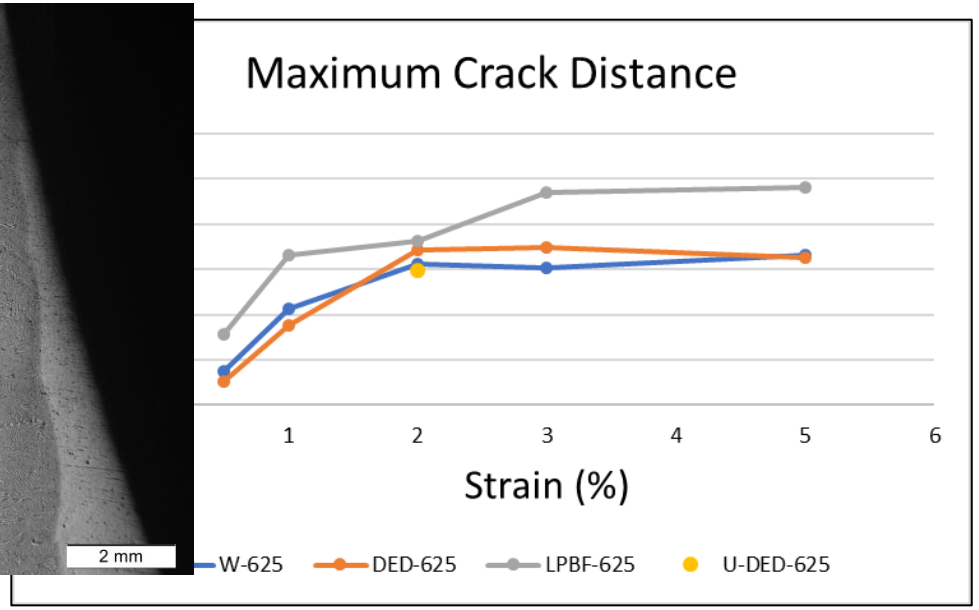
Ni – 625 Transverse Varestraint Results

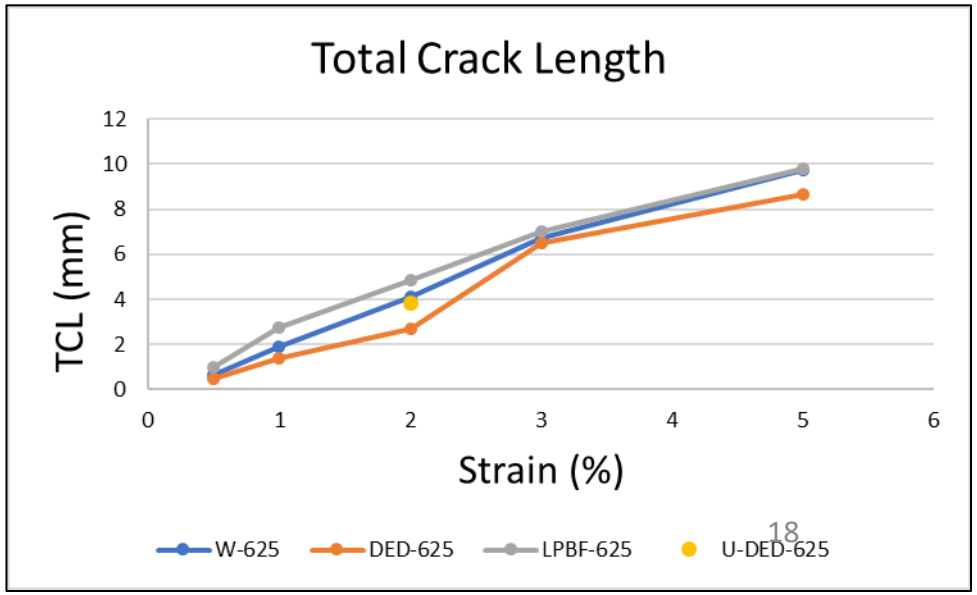






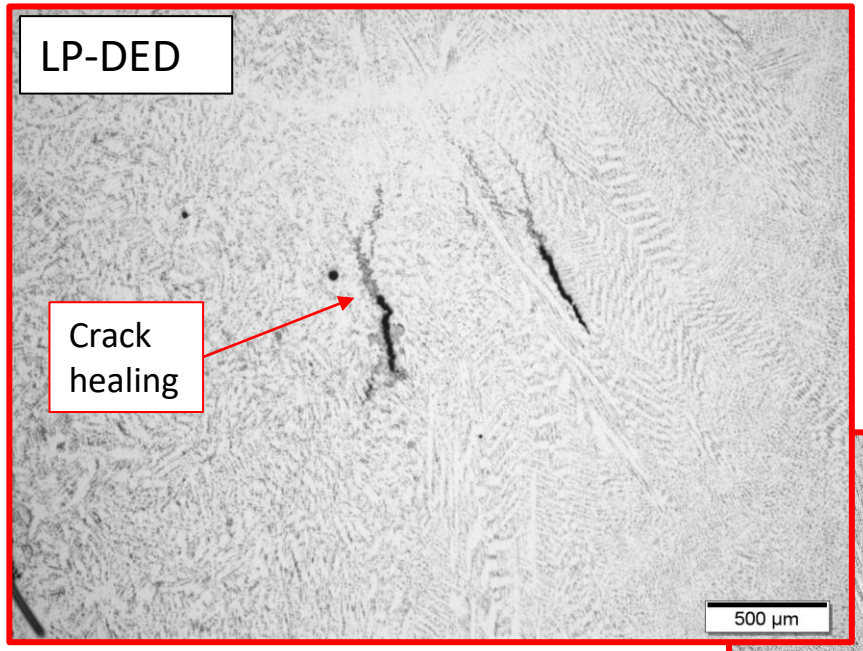


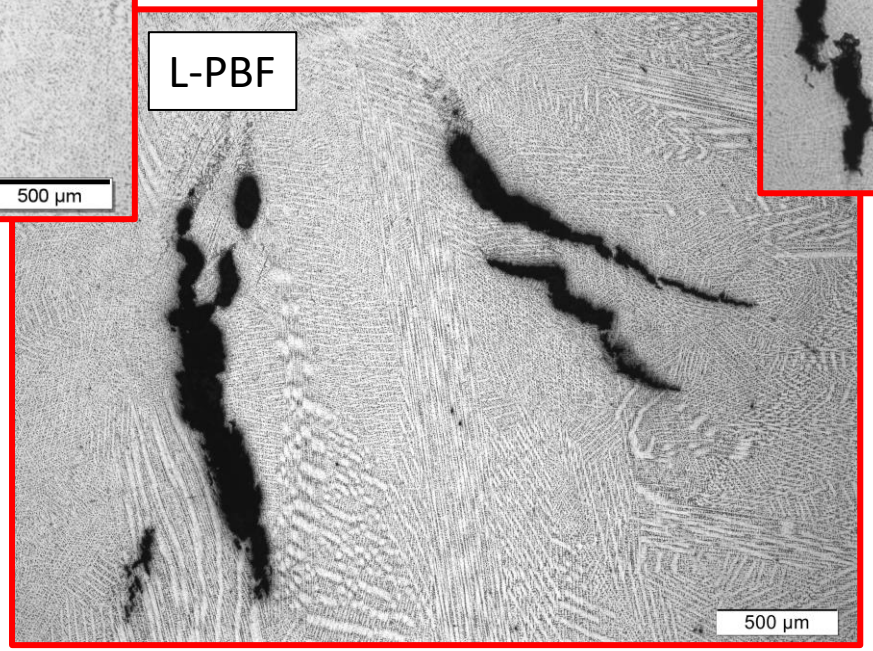


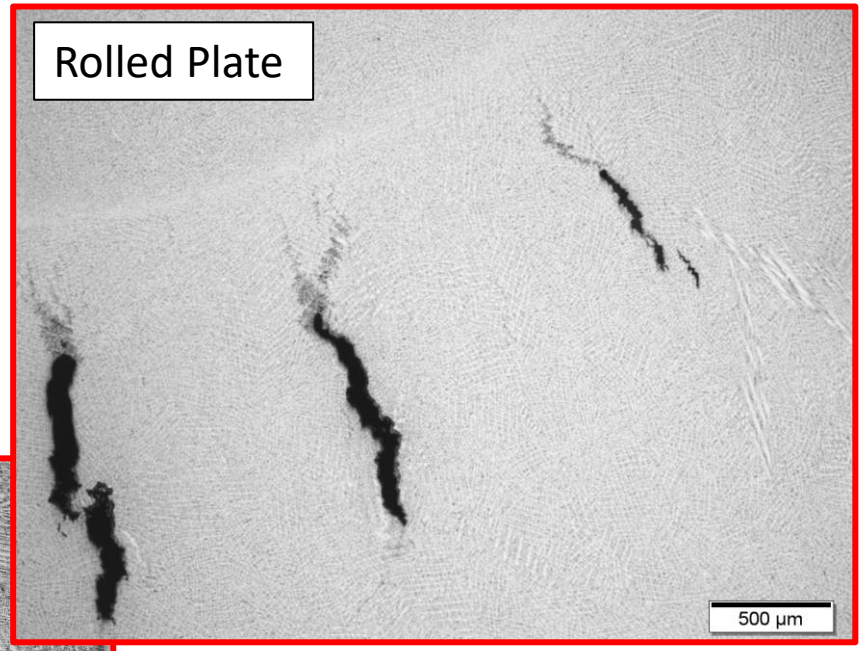


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Ni – 625 Transverse Varestraint Results







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Result Discussion

- Results for 718 show that DED material had the most severe cracking response to trans-varestraint testing
  - This is most likely due to the larger grain size
- Previous welding research has shown that grain size plays a major role in a material's weldability [1,3,4]
- The results of Ni-625 show that all 3 material types trend quite well together
  - This implies they will weld similarly
  - PBF material appears to have fewer cracks but a larger individual cracks (exaggerating the effect of MCD)
- Both materials exhibit grain boundary wetting and some level of crack back filling
  - Weldability testing exacerbates real world cracking mechanisms, does not allow time for crack healing to occur
- The total number of cracks and total crack length for both materials trend well
  - This leaves MCD as the best method to compare within a single material

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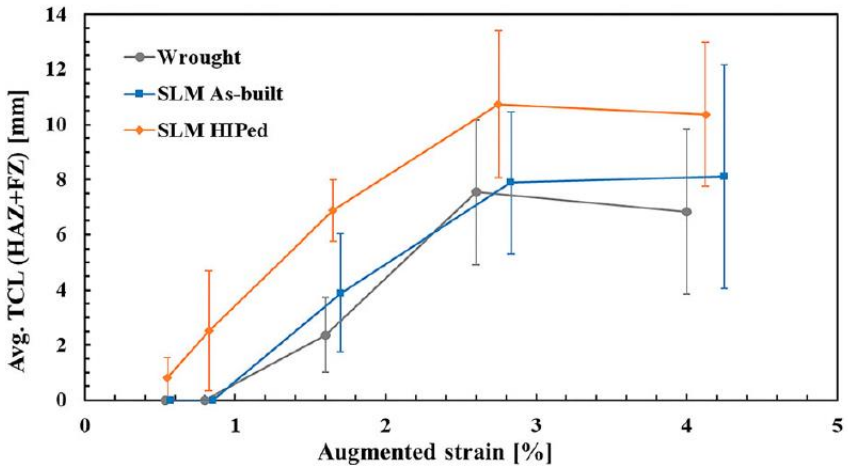
Varestraint Testing in Literature (Tahira Et Al.) [5]

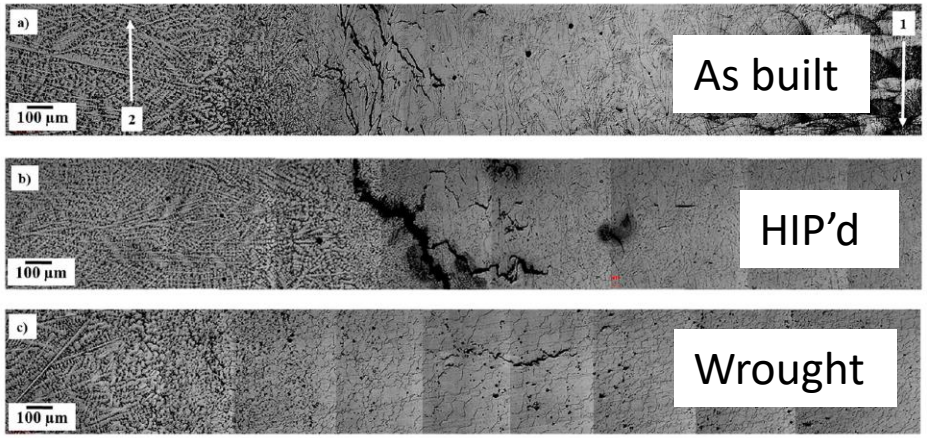
Examined SLM built 718

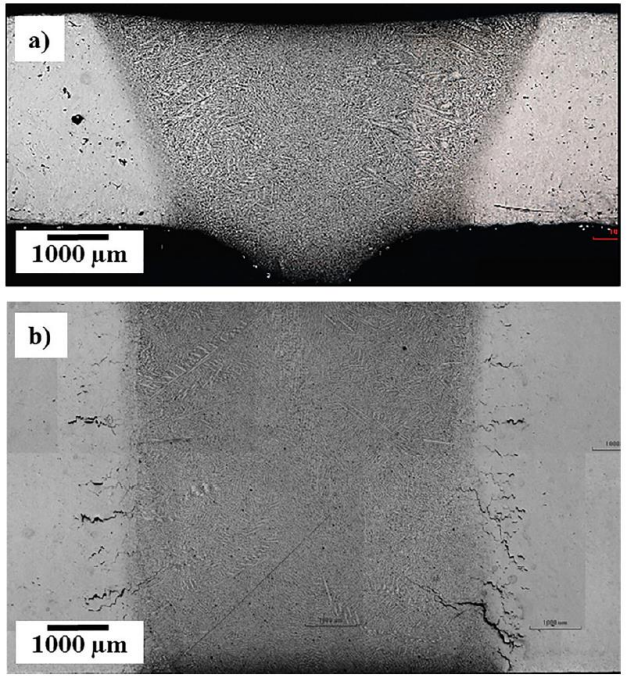
- 3 conditions tested: As built, HIP'd, and off the shelf wrought
- Tested 3 plates per condition 15 plates per material
  - Specimen size was 50 mm x 100 mm x 3.4 – 3.2 mm (NASA used 3.2 mm)
  - Tested from .5% - 4% augmented strain

Results

- Saw worst cracking in the HIP's samples due to grain growth
- As built matched wrought 718

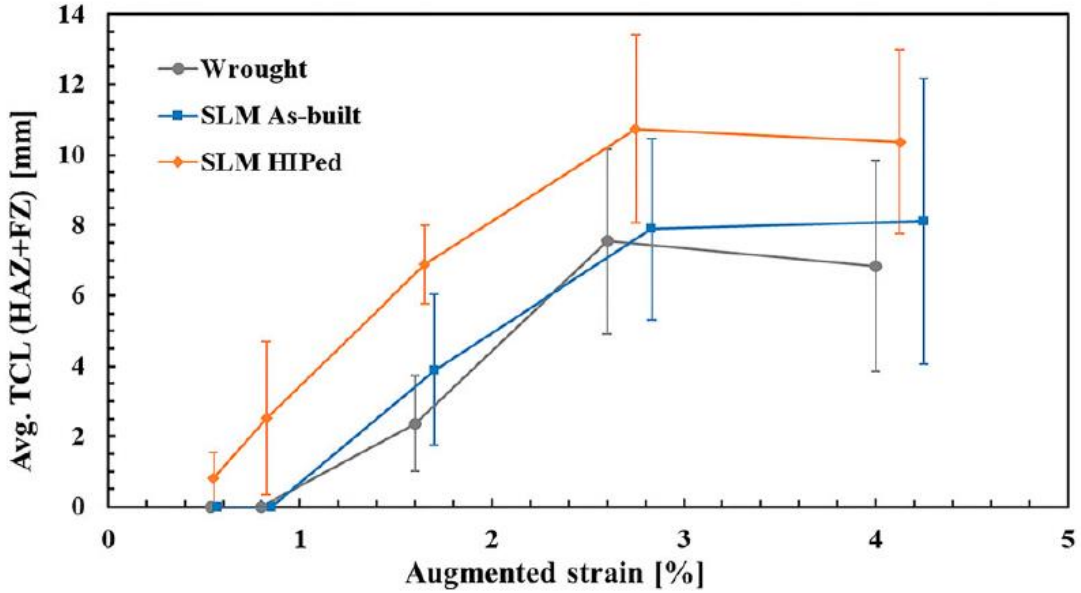




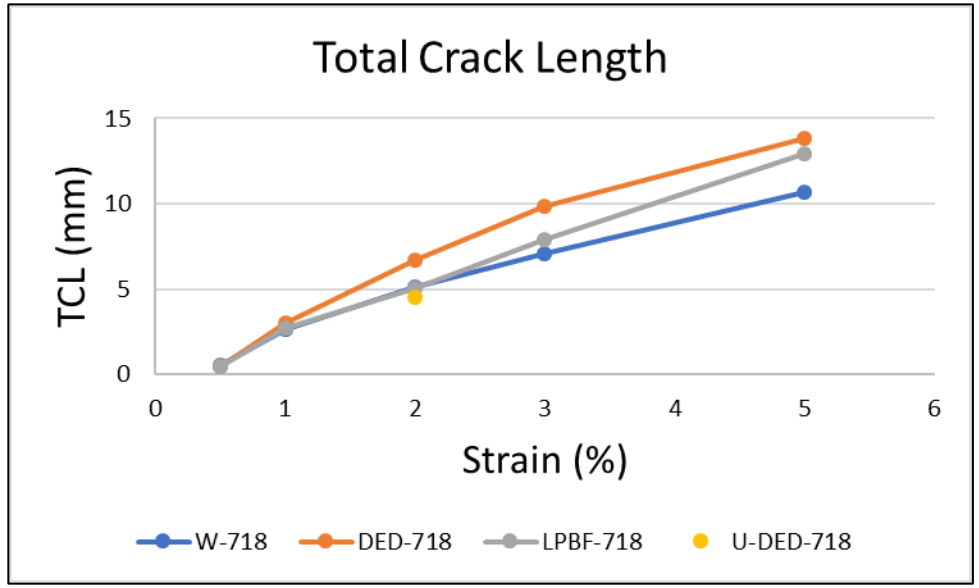


Data Comparison with Literature

Tahira et al. 718 TCL



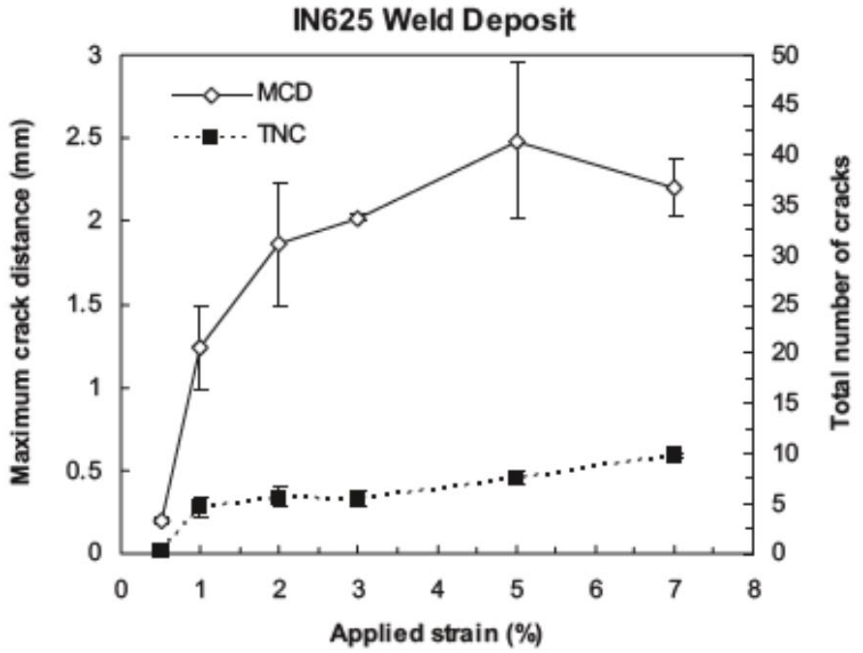
NASA 718 TCL



- Two Different Tests, Varestraint vs. Trans-Varestraint
- Both show that cracking trends with grain size

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Results in Literature – Ni 625



[2] Lippold, J. C., Sowards, J. W., Murray, G. M., Alexandrov, B. T., & Ramirez, A. J. (2008).

[6] M. J. Cieslak

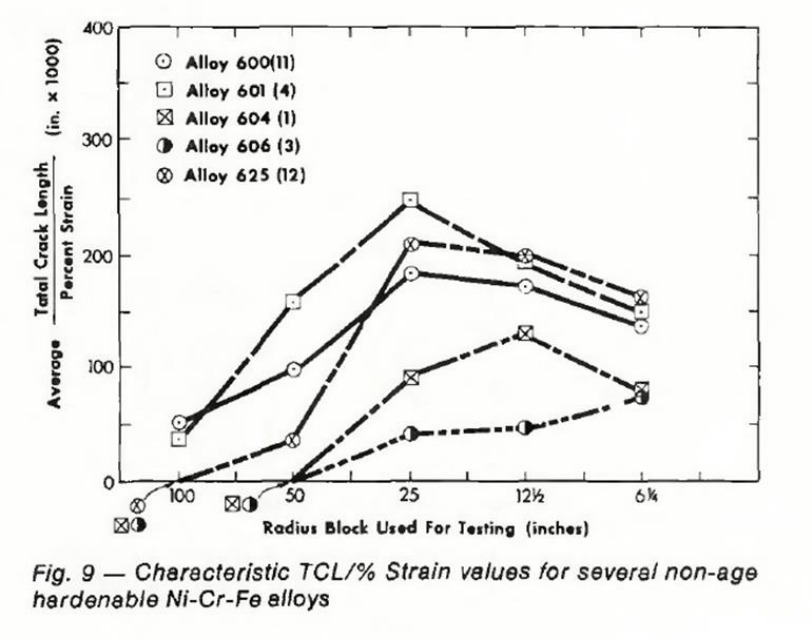
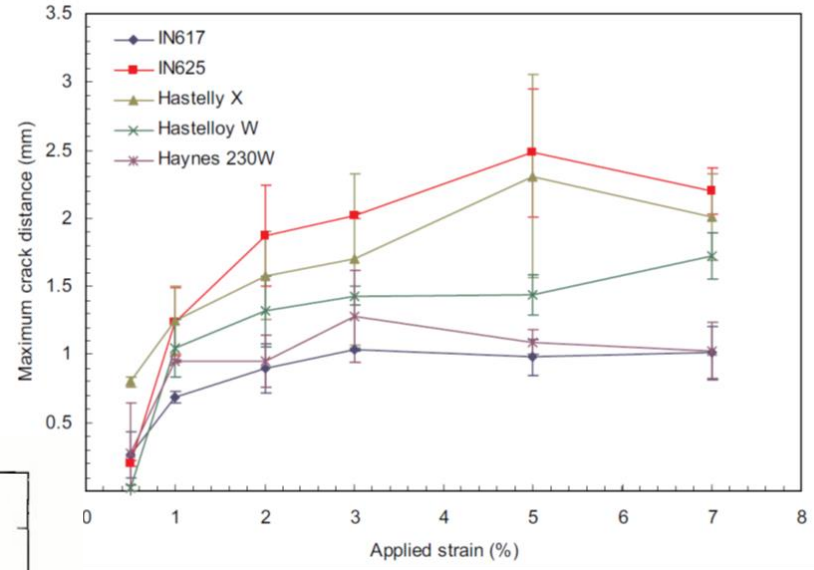
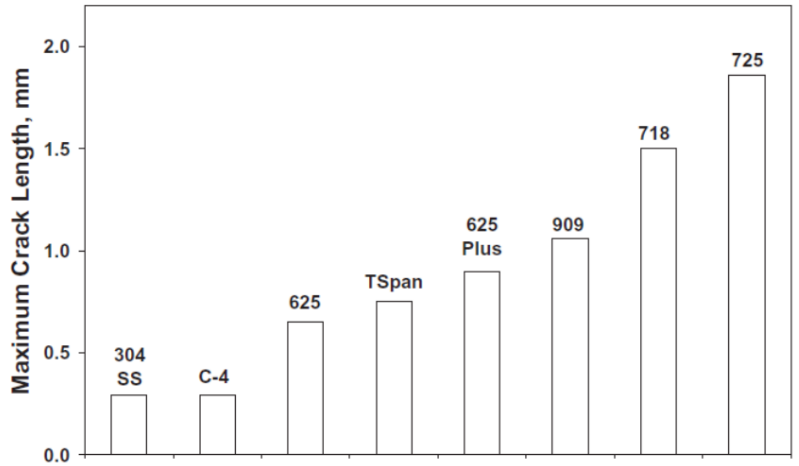


Fig. 9 — Characteristic TCL/% Strain values for several non-age hardenable Ni-Cr-Fe alloys



- NASA's recent study shows MCD at 2% between 1.5-2 mm
- AM material having a higher MCD than traditional material

Data from Welding Metallurgy and Weldability of Ni-Based Alloys [7]



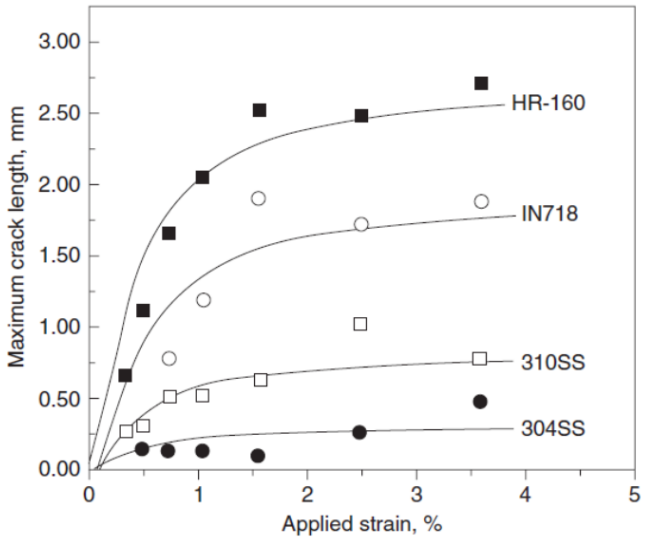


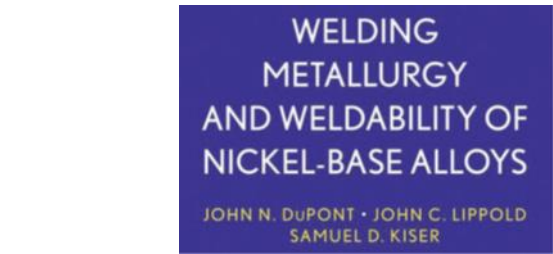
TABLE 3.15 Ranking of Solidification Cracking Susceptibility based on Varestraint Data.

* See Ref Slide

Alloy	Varestraint MCL or MCD (mm)	Reference
B-3	0.3–0.5	1,2
B-2	0.5	2
59	0.5	2
C-276	0.5–0.7	1,2
686	0.6	2
C-22	0.7–1.0	2,3
617	1.0	4
230W	1.1	4
214	1.1	1
625	1.2–2.2	1,2,4
W	1.5	4
Waspaloy (1)	1.5	1
718 (1)	1.75	5
X	2.0	4
HR-160	2.5–3.0	1,5

- At 2% strain NASA saw the respective MCD Results:
  - 625 – 1.5-2mm
  - 718 – 1.5 – 3 mm

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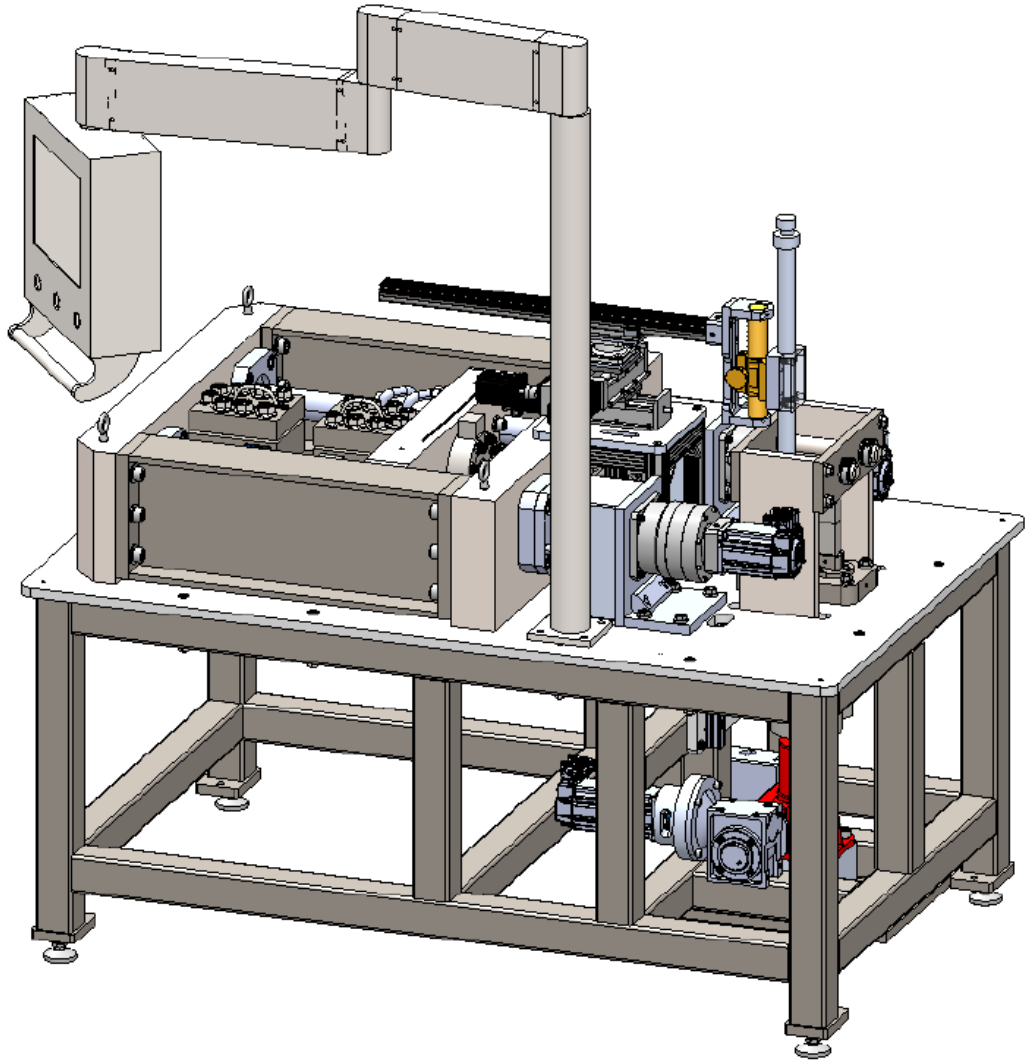
Conclusions

- **Cracking distances at the threshold strains were low for all material forms**
  - Both alloy shows promising weldability when used in AM condition
  - Major differences were observed at higher strain levels between material produce form
- **The weldability response for Ni 718 showed that all three material formats reached threshold strain at the same strain rate (2%) with the LP-DED material exhibiting the largest maximum crack distance.**
- **The weldability response for Ni 625 showed that L-PBF built material reached threshold strain quicker than the LP-DED and Conventional plate material and also exhibited a larger maximum crack distance compared to the other material forms with the LP-DED material tracking closely with the conventional Ni 625 plate material.**
- **Surface Finish controls puddle shape and can cause arc wander during welding**
- **Both alloys showed crack backfilling (Crack Healing)**

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Weldability Testing at NASA MSFC

- Modernized weldability tester designed and produced by Ohio State University's Center for Design and Manufacturing Excellence (CDME)
  - Operates using servo motors instead of hydraulic motors for better performance and improved machine maintenance
- This system contain a **Varestraint** test system and a **Controlled Tension Weldability** test system
- Welding process agnostic (mostly)
  - Set up for GTAW torch
- Current materials to be tested
  - NASA HR-1
  - 6061-RAM2
  - NASA GRX-810



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Welding Case Study

RAMFIRE Aluminum Rocket Nozzle

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RAMFIRE Background

- **Place Holder for ER14 provided background info**

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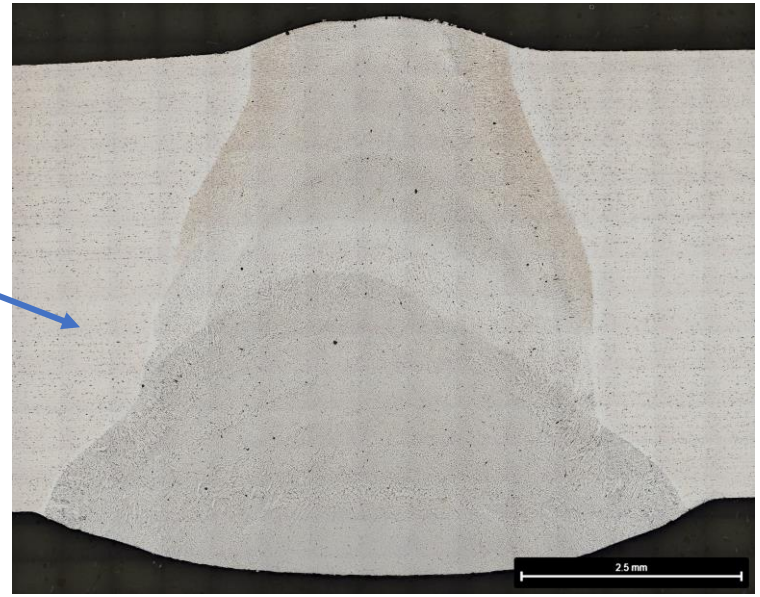
Welding Processes on RAMFIRE

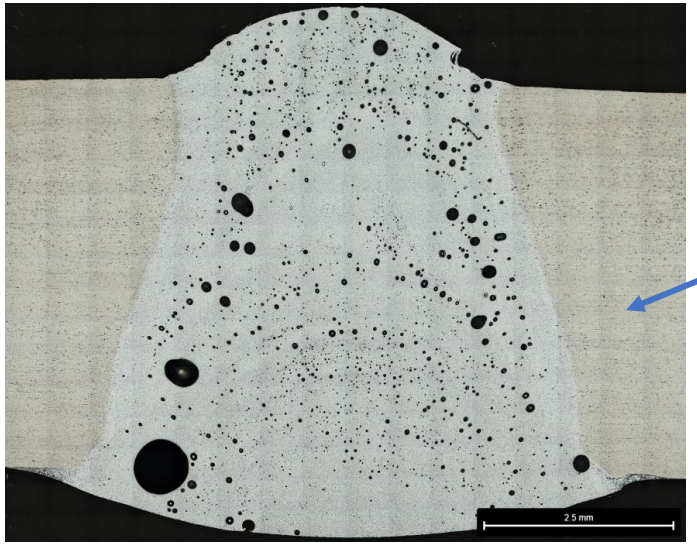
- **Place Holder for overview of nozzle**

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6061 – RAM2 Weld Wire Testing at MSFC

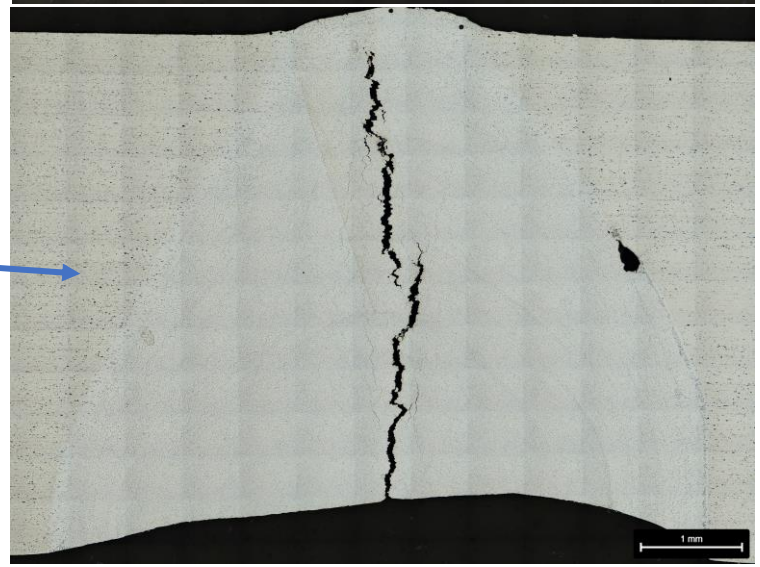
Base: AA 6061 –T6
Filler: AA 4043

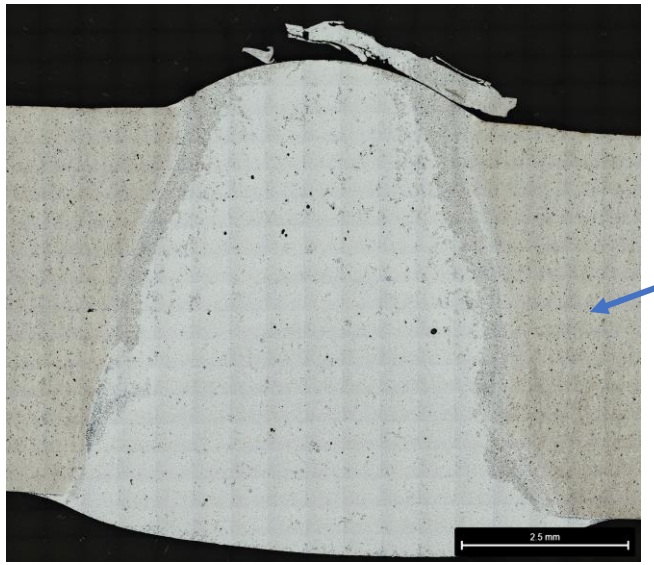




Base: AA 6061 – T6
Filler: Dev. RAM2

Base: AA 6061 –T6
Filler: 6061 wire

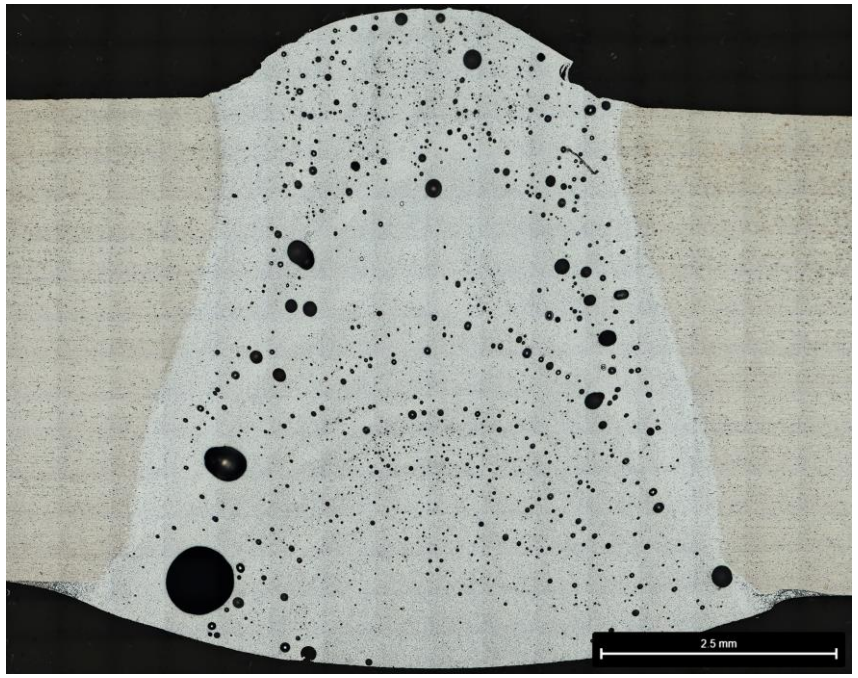




Base: AA 6061 – RAM2
Filler: 6061 wire

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RAM Wire Developments



External vendor drawn wire, poor cleanliness. No Cracking!

Wire Used on RAMFIRE Nozzles

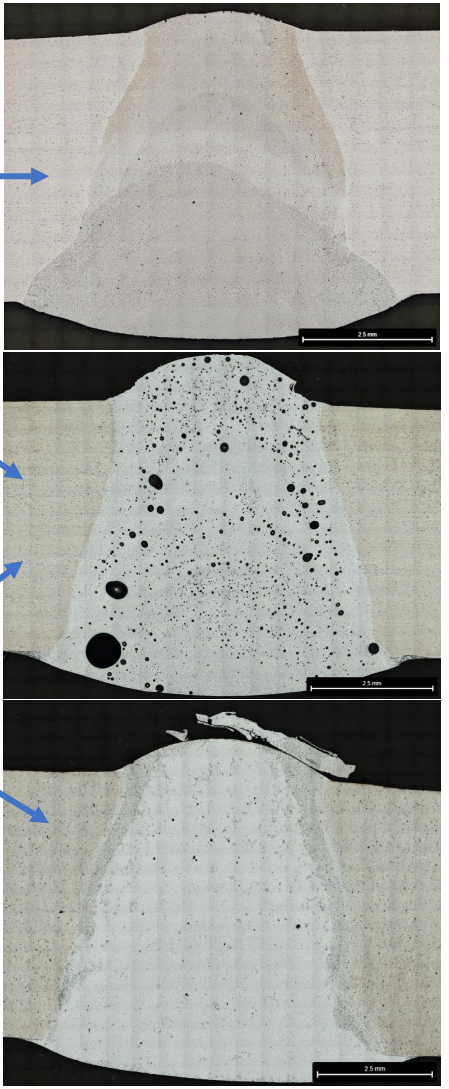


Fortius Metals produced RAM2 wire. Acceptable porosity, no cracking!

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RAM Wire Mechanical Testing

	EM22 Specimen ID	Other Specimen ID	Tensile Stress (KSI)	Yield Stress (KSI)	Modulus of Elasticity (MSI)*	Fracture Elongation (%)
4043 Wire	220108014	Weld 1-T1	30.21	18.24	9.60	8.83
	220108015	Weld 1-T2	29.10	17.42	9.26	8.89
	220108026	Weld 4-T1	29.25	18.83	9.41	6.10
	220108027	Weld 4-T2	29.29	19.00	9.57	7.47
	220108030	Weld 5-T1	23.78	18.94	8.91	1.92
	220108031	Weld 5-T2	30.13	18.87	10.15	7.49
RAM Filler Metal	220108034	Weld 6-T1	23.93	18.48	10.31	1.83
	220108035	Weld 6-T2	23.32	18.33	9.55	1.94
	220108038	Weld 7-T1	28.74	18.73	10.12	5.79
	220108039	Weld 7-T2	28.46	18.27	9.91	9.14
	220108042	Weld 8-T1	29.13	18.57	9.27	8.89
	220108043	Weld 8-T2	29.09	18.51	10.36	8.42
	220108046	Weld 9-T1	31.17	24.82	10.84	1.16
RAM Base/Filler Metal	220108047	Weld 9-T2	30.54	24.52	10.90	1.41
	220108050	Weld 10-T1	29.97	24.17	10.85	1.21
	220108051	Weld 10-T2	30.32	22.79	9.94	1.48
RAM Base/ 6061 Filler Metal	220108054	Weld 11-T1	37.38	26.36	10.65	8.09
	220108055	Weld 11-T2	37.26	24.93	10.72	13.61

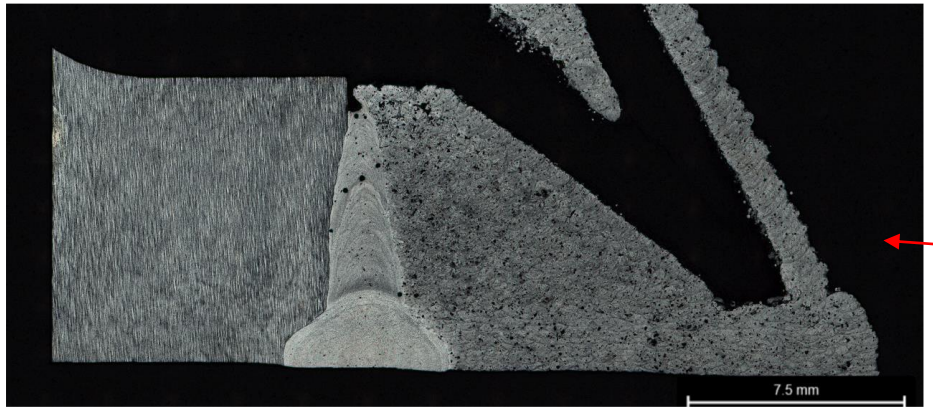


Major Observations:

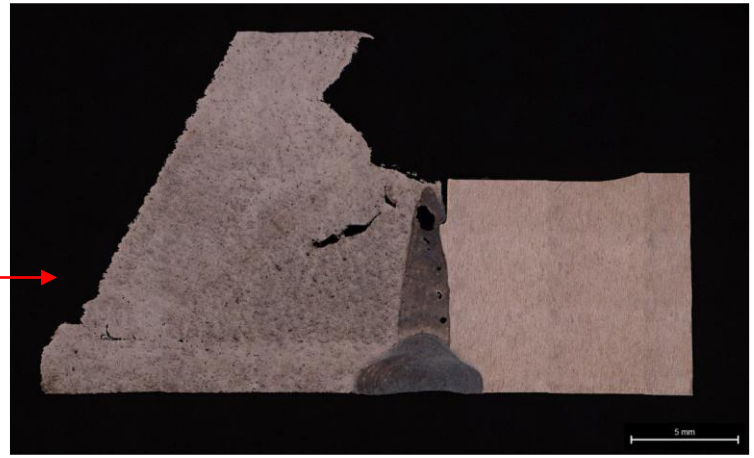
- Poor porosity caused low elongation values
- Majority of welds with RAM2 welds performed similarly to 4043 in UTS
- Defect free weld with RAM2 base metal exhibited favorable mechanical properties

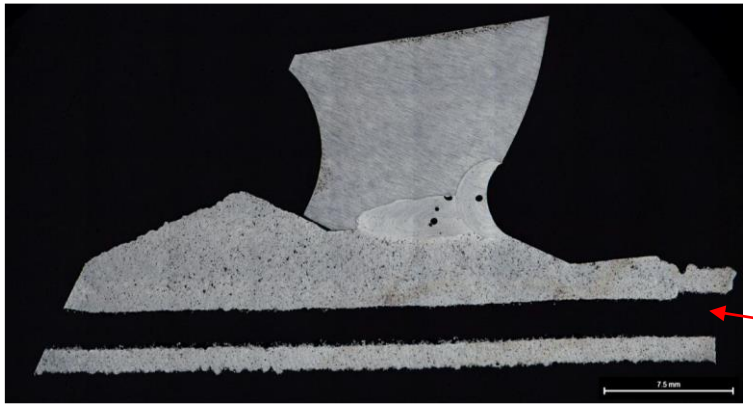
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Electron Beam Welding













All welds autogenous Wrought 6061-T6 to 6061 – RAM2 DED material. No weld cracking observed, some porosity and root tip defects identified.

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Acknowledgements

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  - **Bryan Lara**
  - **Benjamin Sutton**
- Thanks to **Tessa Fedotowsky**, **Ben Williams** and the rest of the RAMFIRE team!

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* See Slide 20

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Questions?

William.c.evans-1@nasa.gov