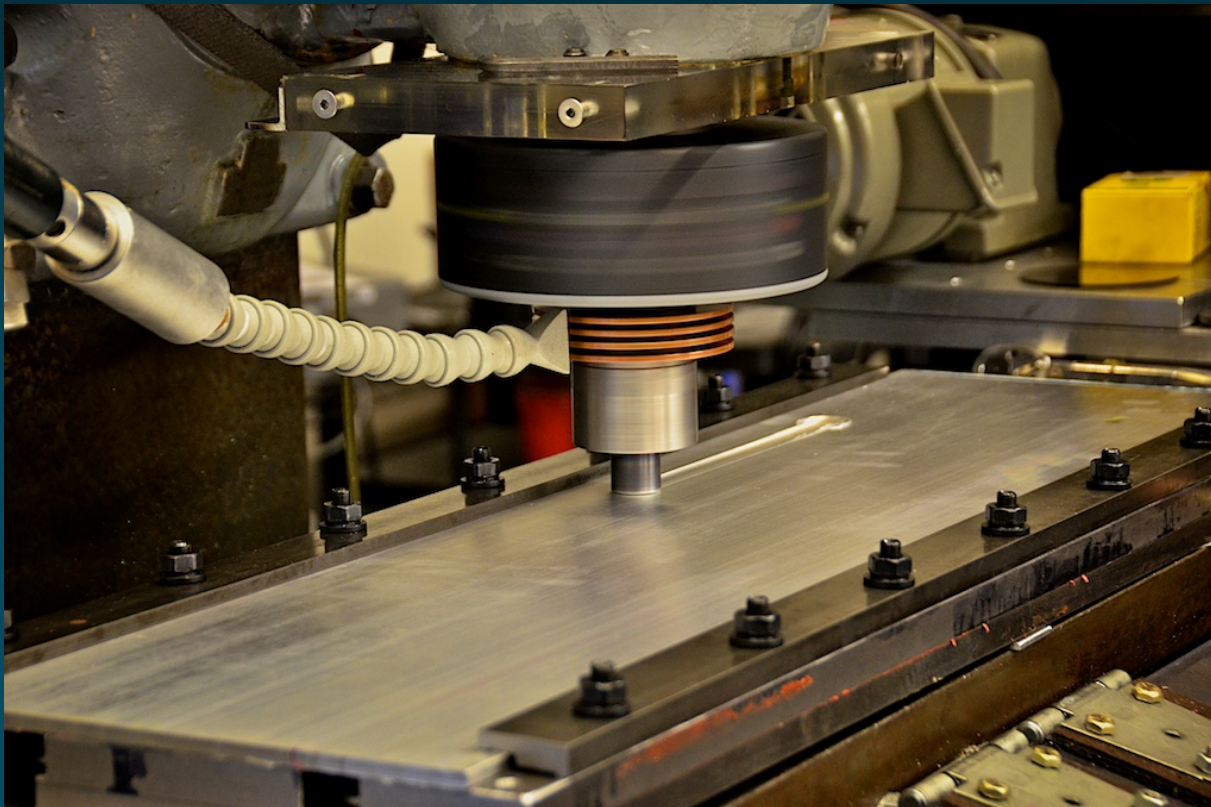


Friction Stir Welding of Additively Manufactured Aluminum Alloys

William T. Evans, Al M. Strauss, George E. Cook, Tracie
Prater

Vanderbilt University Welding Automation Laboratory
(VUWAL)



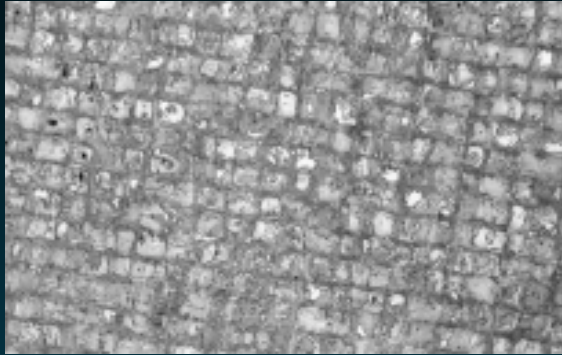
Why Additive Manufacturing?



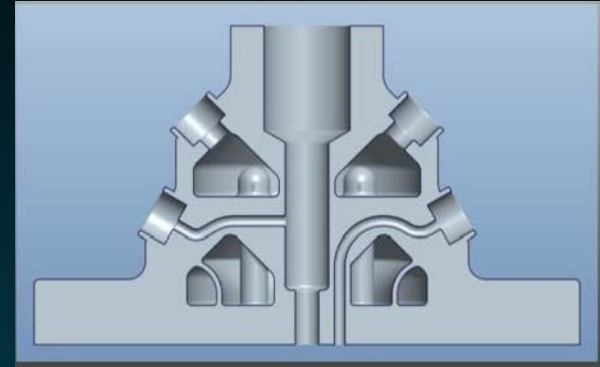
*RS-25 (space shuttle main engine) flex joint redesigned with selective laser melting. Part count reduced from 45 to 17 and number of welds reduced from 70 to 26
Image credit: NASA.*

- **Produce near net-shape monolithic parts that reduce the part count and number of welds in an assembly**
- **Enable rapid iteration of the design/build/test loop to accelerate new hardware development**
- **Impart significant cost and time savings for certain hardware applications**
- **Flexibility in design and delivery of feedstocks (ex. custom blends and functionally gradient materials)**

Primary Challenges in AM



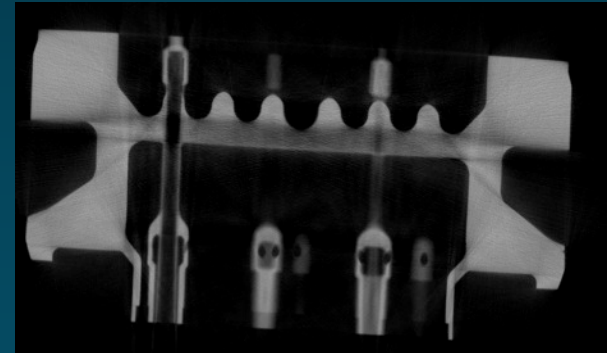
Materials
Characterization



Standard Design Practices



Process Modeling,
Monitoring, & Control



Certification

Additional Challenge for AM: Welding

- Limited part size due to size of the build chamber/platform for AM
- There is little published data related to welding of additively manufactured material in the open literature
- Weldability will be impacted by a number of variables which influence material outcomes
 - Machine and Manufacturing Process used- ie processing parameters
 - Feedstock characteristics
 - Material postprocessing



Welding of AM parts is an eventuality.

Therefore, there is a clear need for studies of the weldability of additively manufactured components to themselves or to conventionally manufactured components in assemblies

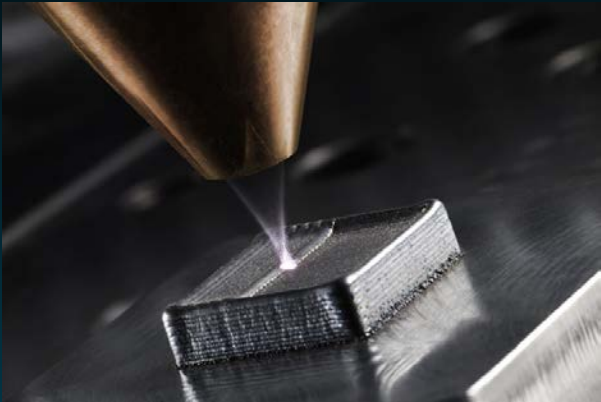
Scope and Objective of Study

Investigate the Friction Stir Welding of additively manufactured Aluminum and assess how the joint properties for these materials compare with welds of conventionally manufactured material

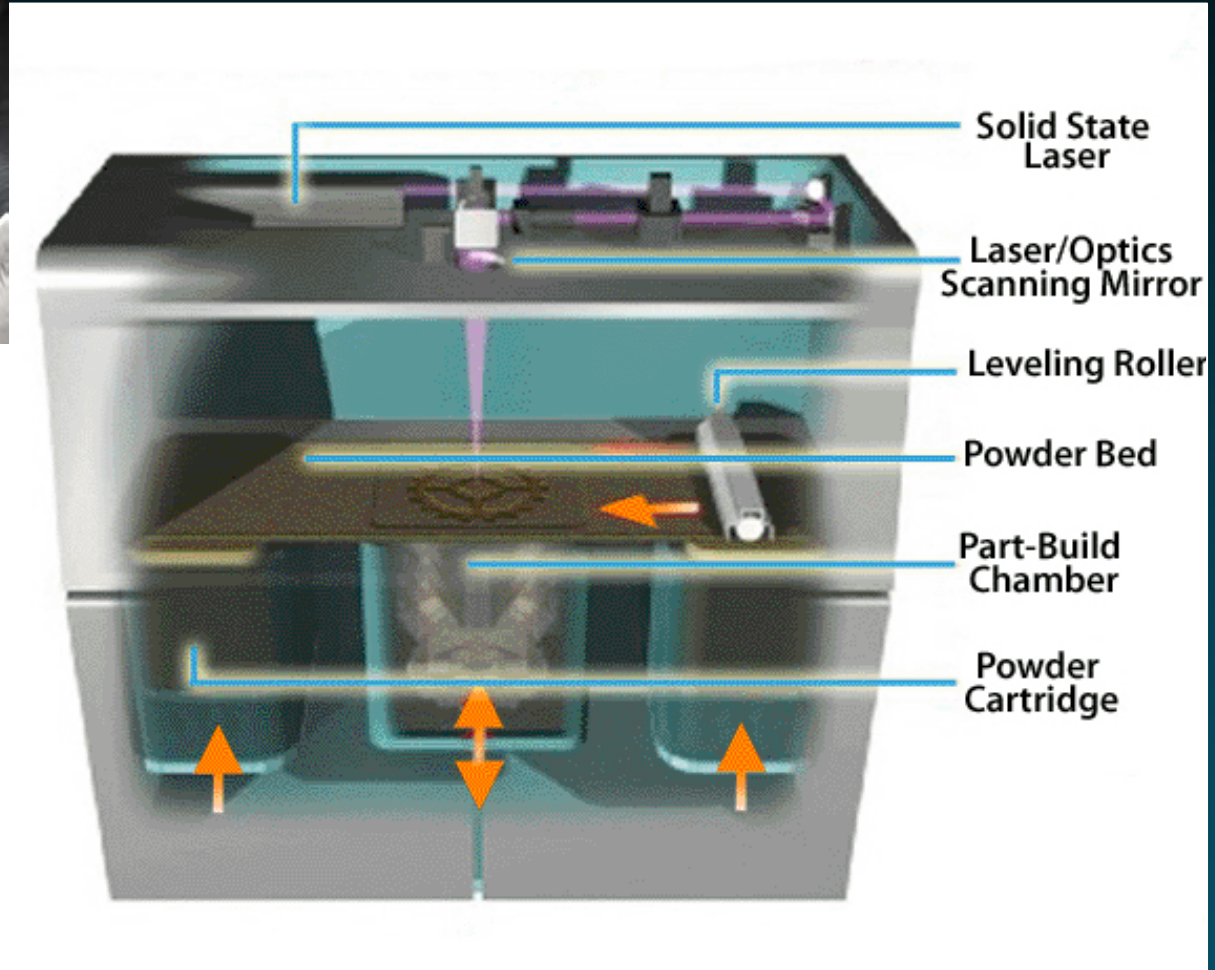
- Compare welds of AM material with parent AM material
- Compare welds of AM material with conventional material
- Initial study of 3 materials produced using 3 different AM techniques

Material	Process	Process type
Al 2219	Electron Beam Freeform Fabrication	Directed energy deposition (metal wire)
AlSi10Mg	Direct Metal Laser Sintering	Powder bed fusion
Al 6061	Ultrasonic additive manufacturing	Sheet lamination

Process Overview: Direct Metal Laser Sintering



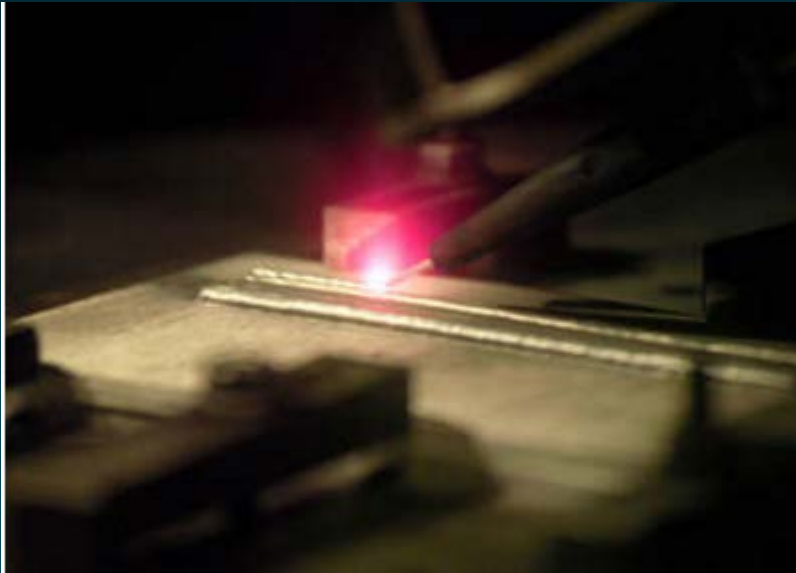
- Thin layer of metal powder is fed onto the build plate
- Laser selectively sinters deposited powder
- Build table is lowered and additional powder is fed onto plate
- Process is repeated layer by layer until part is complete



Process used in this study to produce AlSi10Mg plates

Process Overview: Electron Beam Freeform Fabrication

- Process originally developed by NASA Langley Research Center
- Uses an electron beam and solid wire feedstock to print metal structures
- Requires a vacuum to operate



EBF3 process
Image credit: NASA

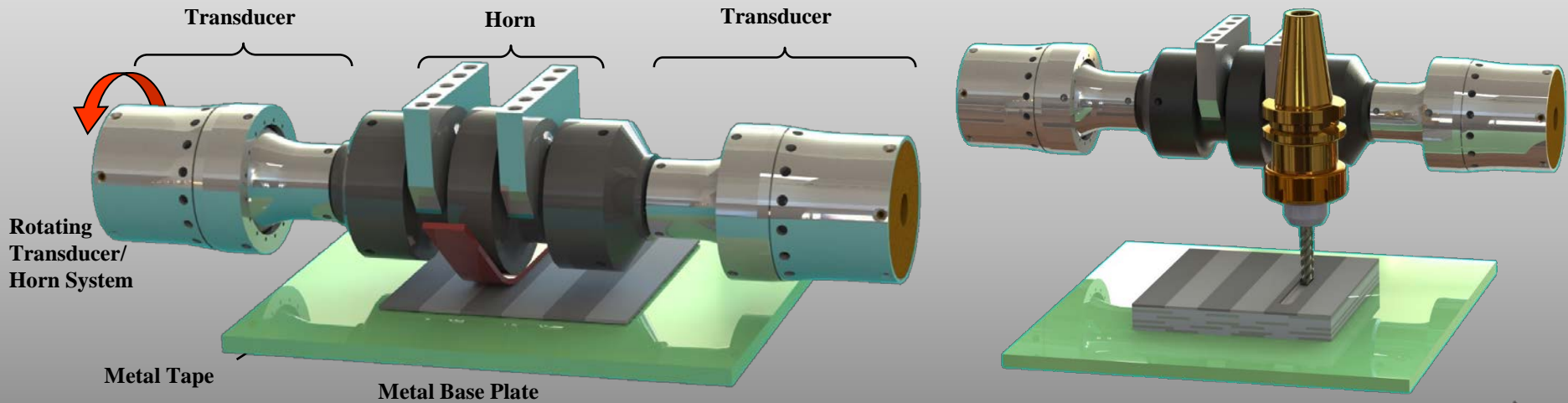


Structural part produced with EBF3
Image credit: NASA

Process used in this study to produce Al 2219

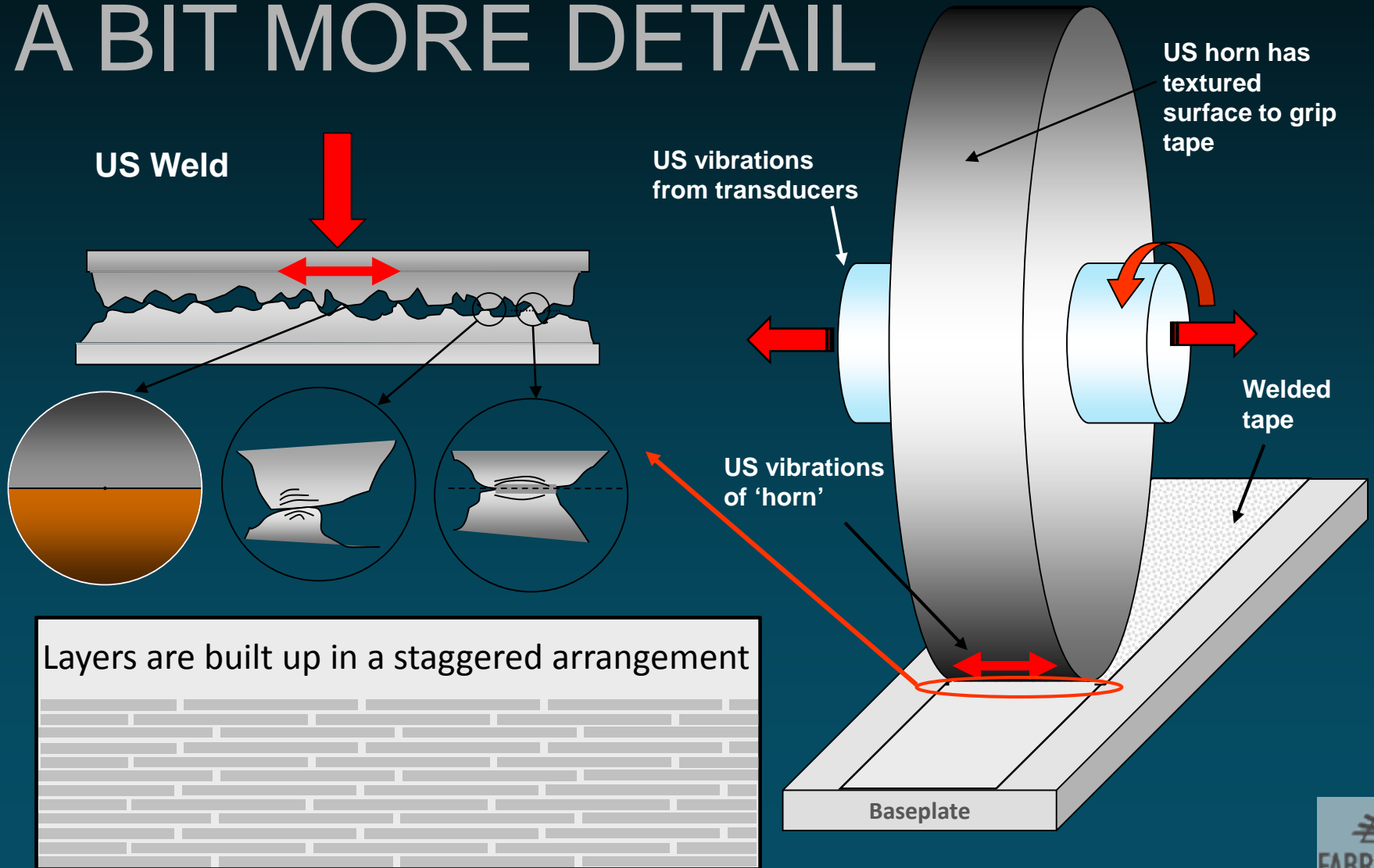
Process Overview: Ultrasonic Additive Manufacturing

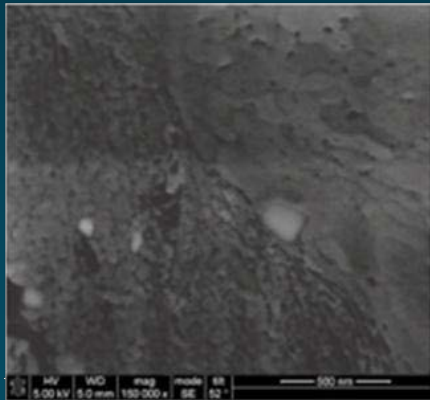
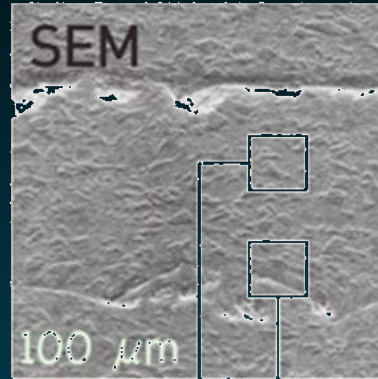
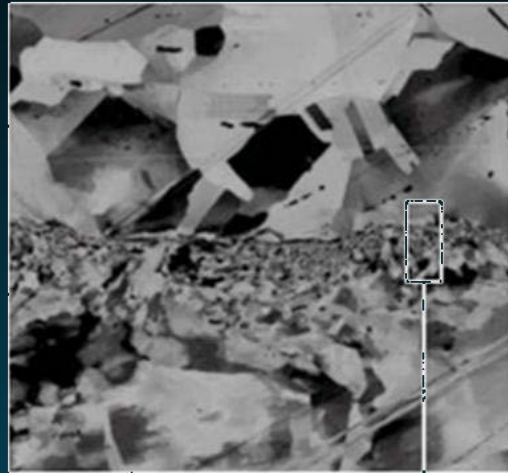
... a new technology – “UAM” creates net-shape solid metal parts using solid state ultrasonic metal welding and CNC contour milling



Process Overview: Ultrasonic Additive Manufacturing

A BIT MORE DETAIL





Metallurgy

- Peak temperatures $<0.5T$ melt
- Solid state process that preserves parent material structure
- Recrystallization at interface
- Local formation of nano-grain colonies
- Can bond dissimilar metals and embed electronics



Materials

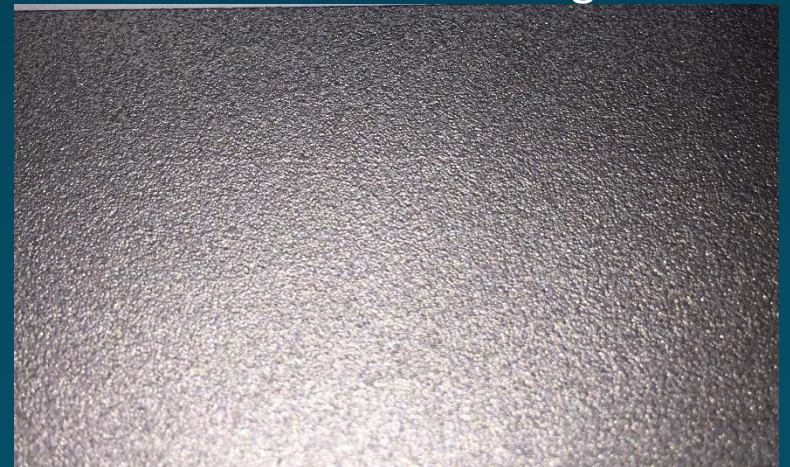
Ultrasonic Additively
Manufactured 6061



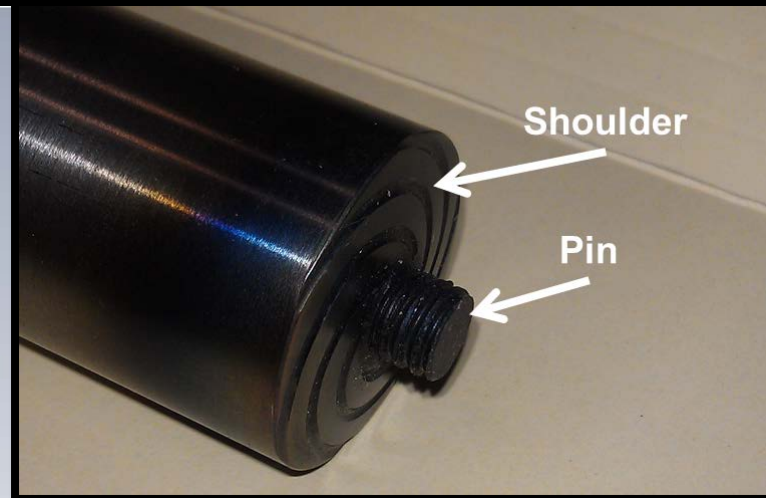
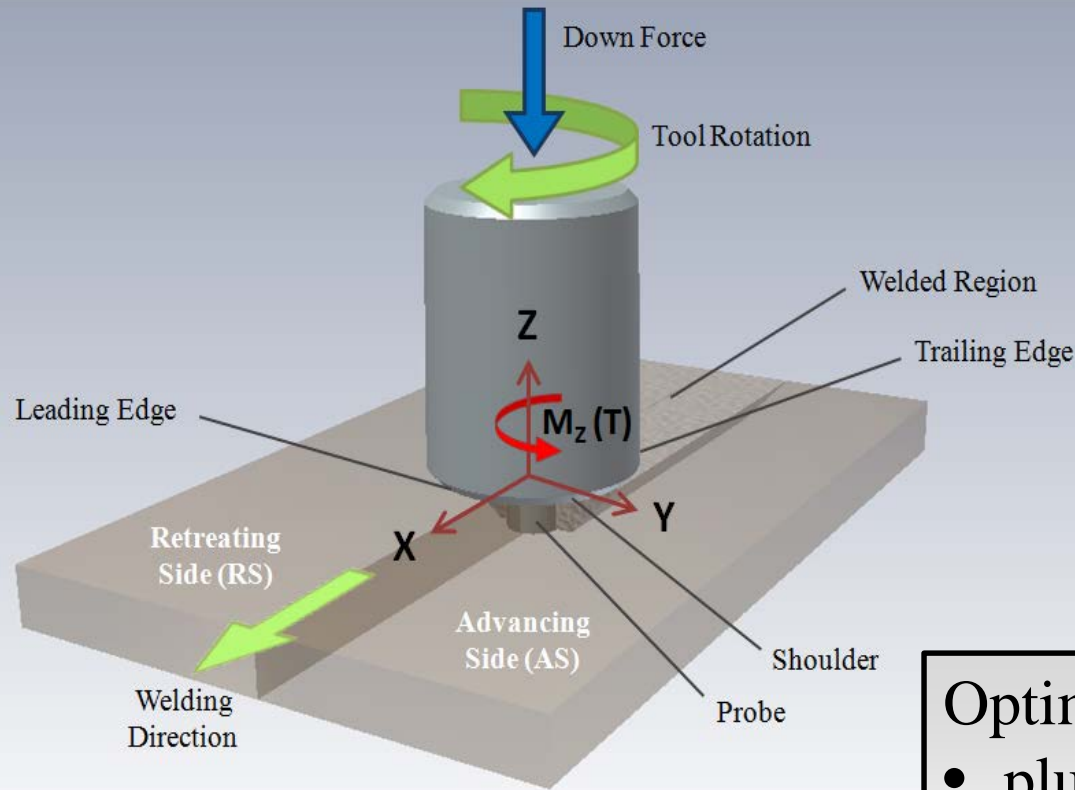
Electron Beam Free
Form Fabrication 2219



Direct Metal Laser
Sintered AlSi10Mg



Friction Stir Welding: Process and Tool Design

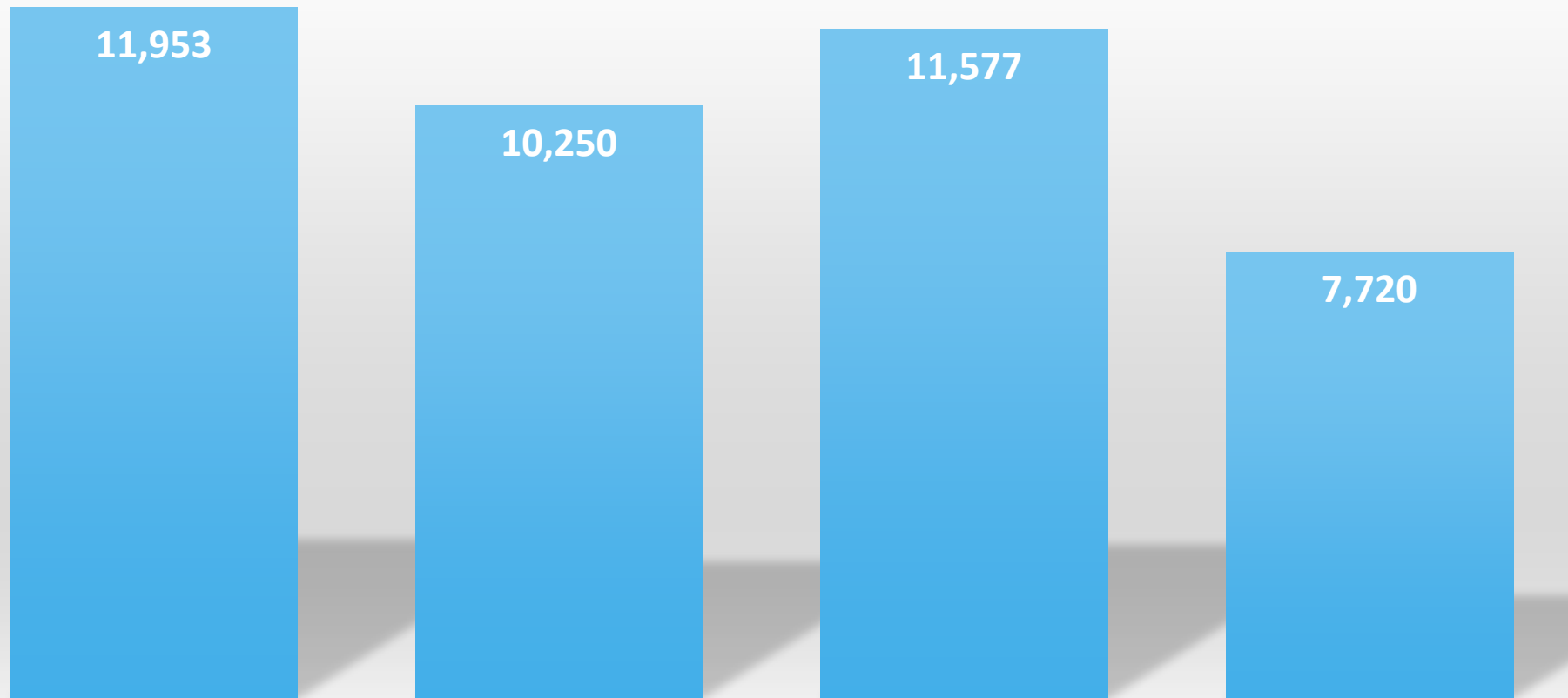


Optimized process parameters:

- plunge depth- 0.2 in.
- traverse speed- 6 ipm
- rotation speed- 1400 RPM

Friction Stir Welding: Ultimate Tensile Strengths for Al 6061 T6

Average Ultimate Tensile Strength(N)
Traditional Rolled Material

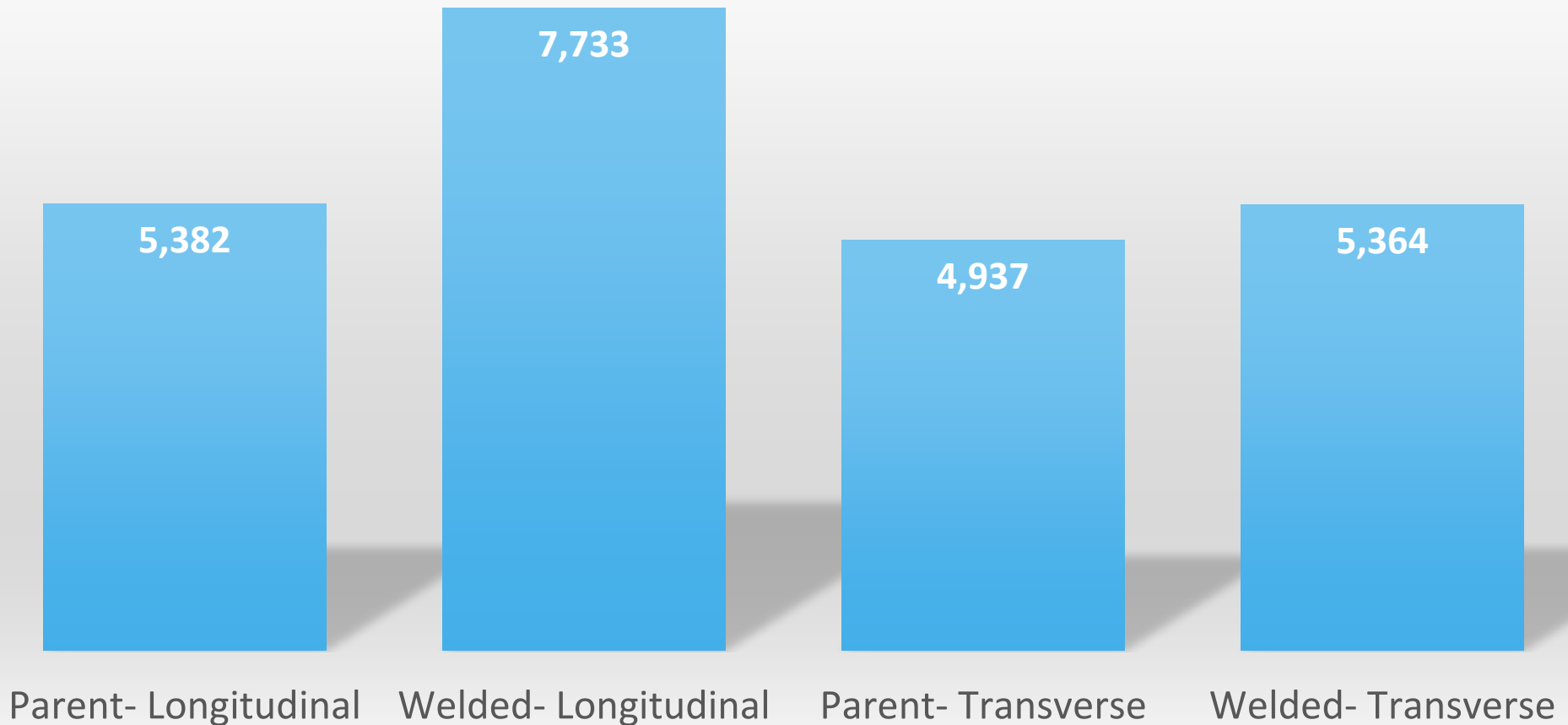


Parent- Longitudinal Welded- Longitudinal Parent- Transverse Welded- Transverse

Rolled AM 6061 is not an appropriate analog for material manufactured with UAM (foil for UAM is in H18 condition)

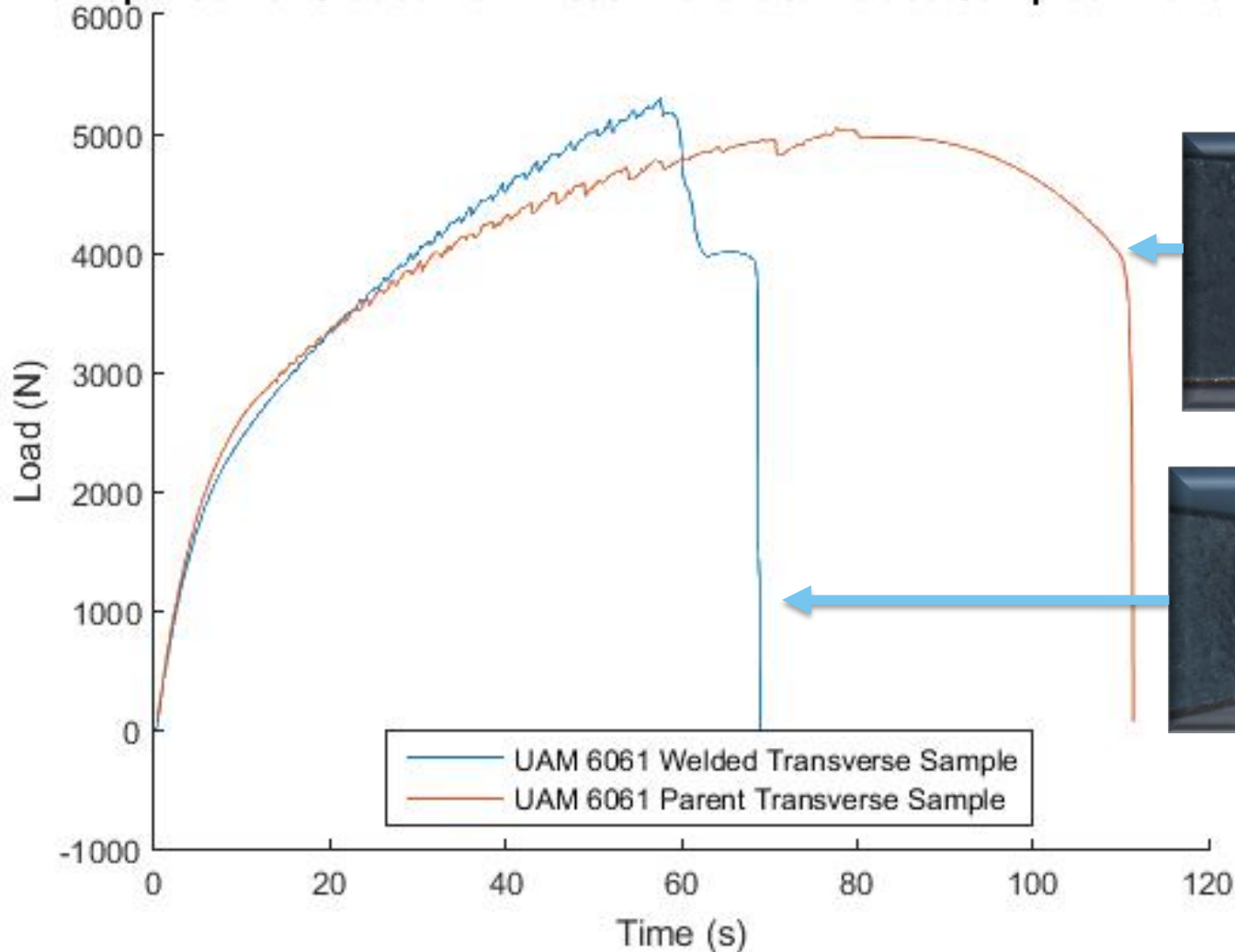
Friction Stir Welding: Ultimate Tensile Strengths for UAM

Average Ultimate Tensile Strength(N)
Ultrasonic Additively Manufactured Material

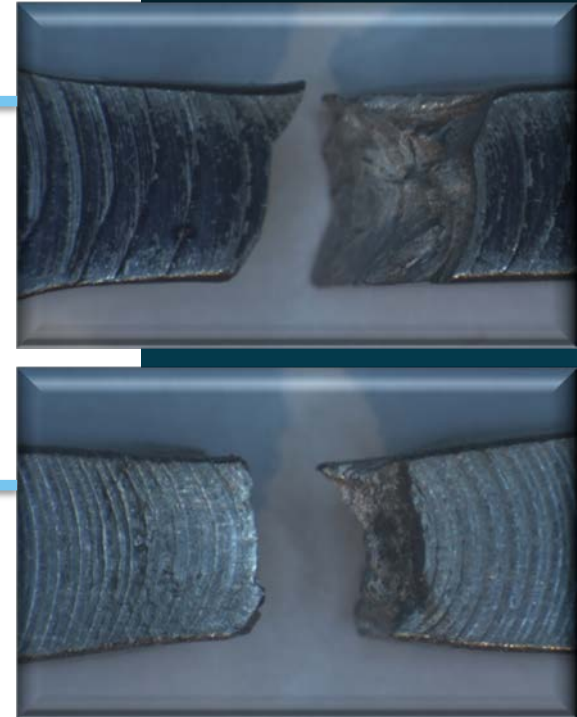
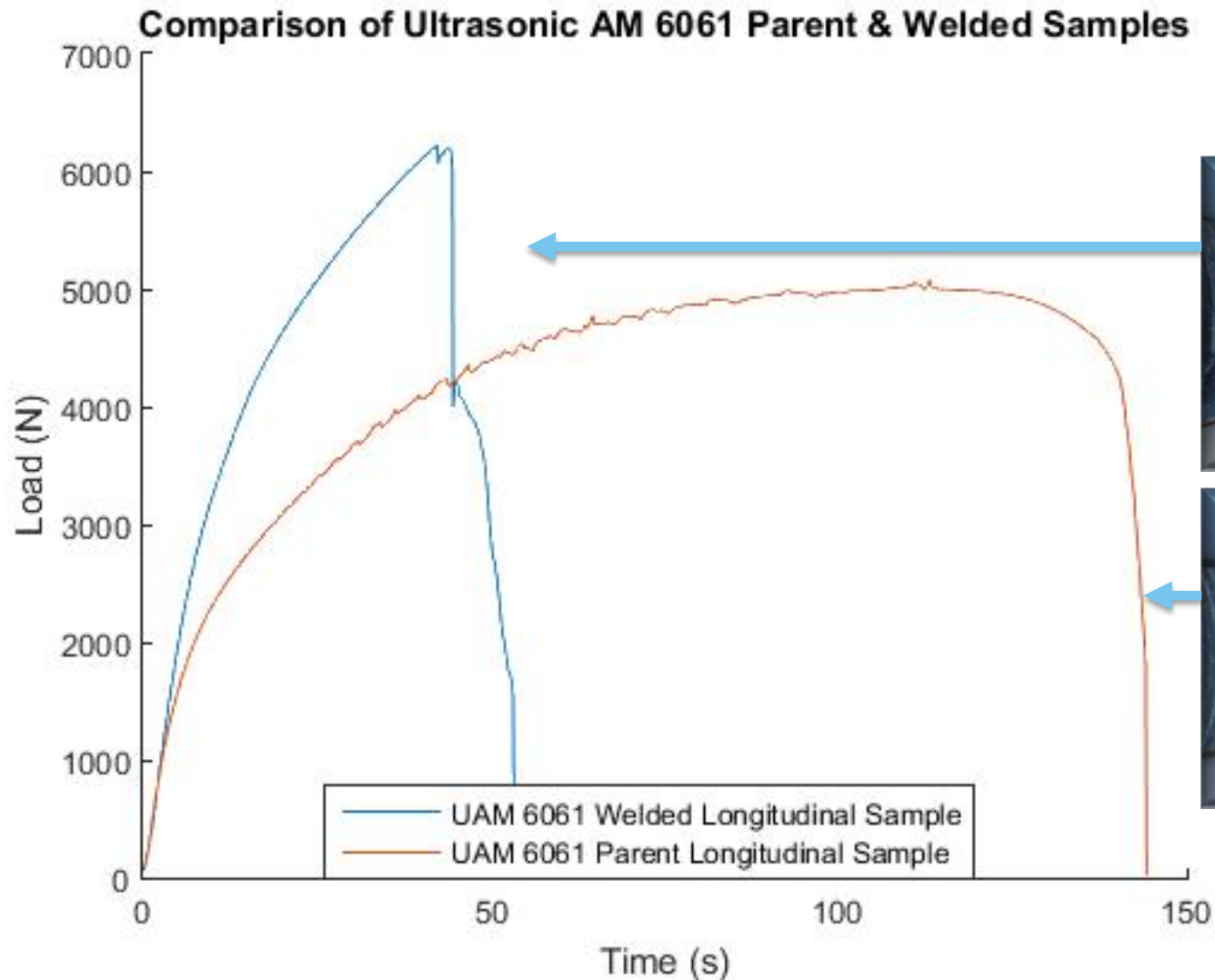


Tensile Results- Transverse Samples

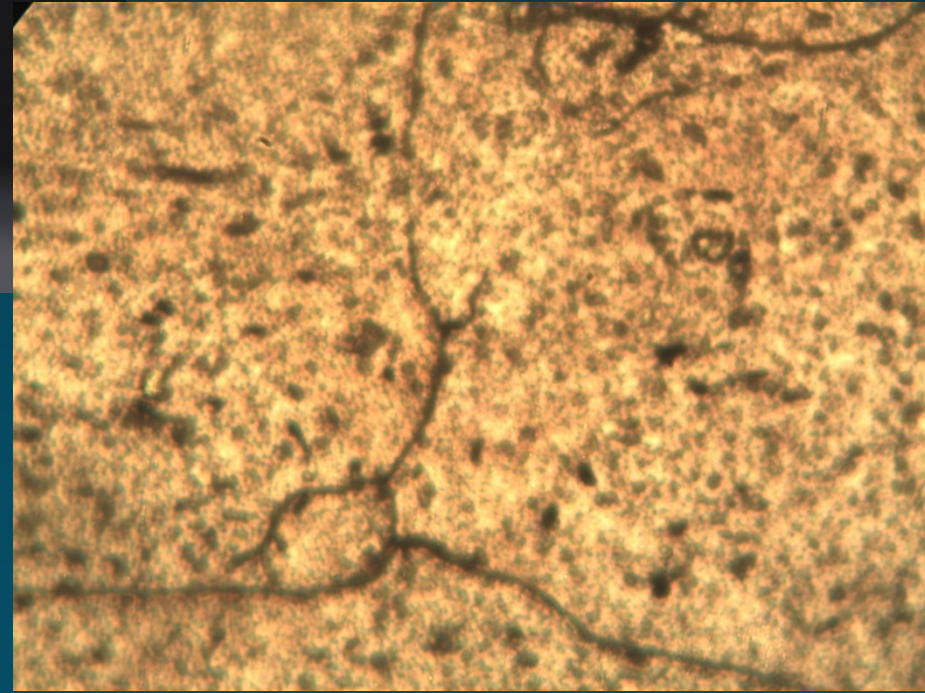
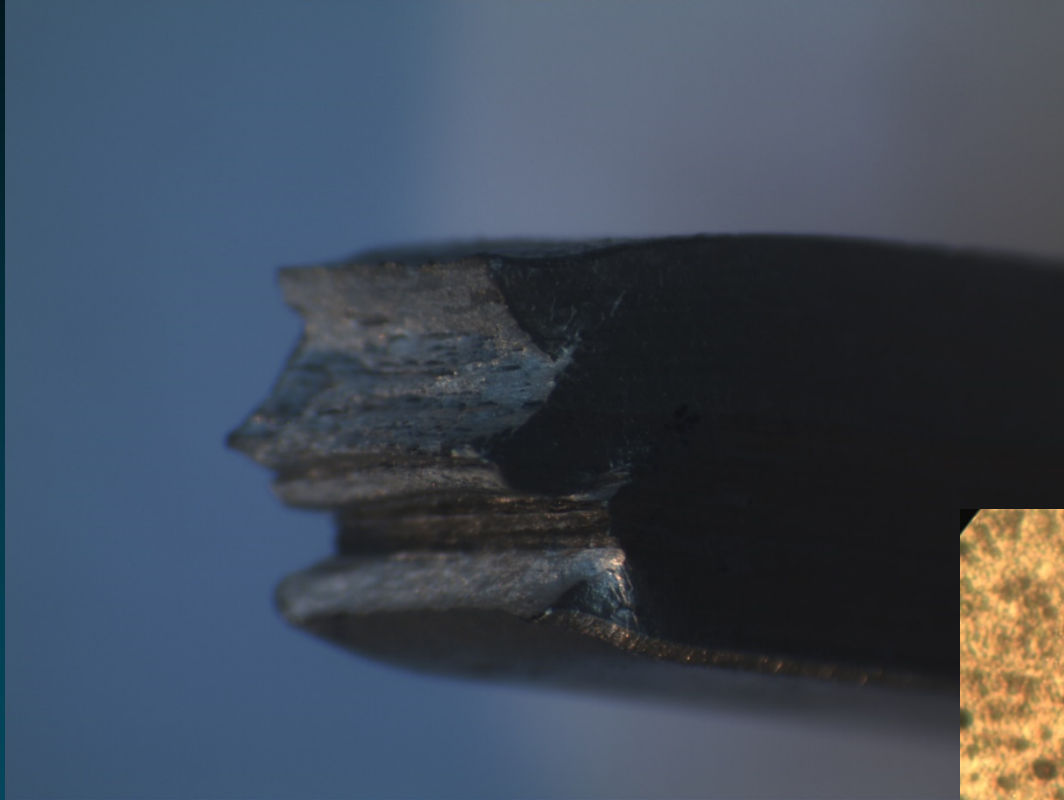
Comparison of Ultrasonic AM 6061 Parent & Welded Samples- Transverse



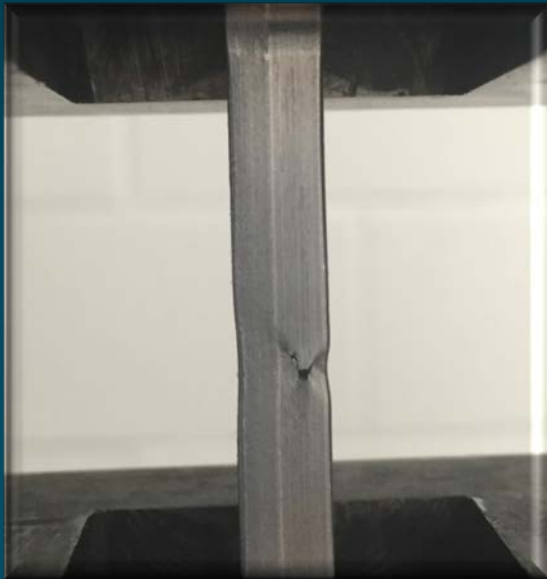
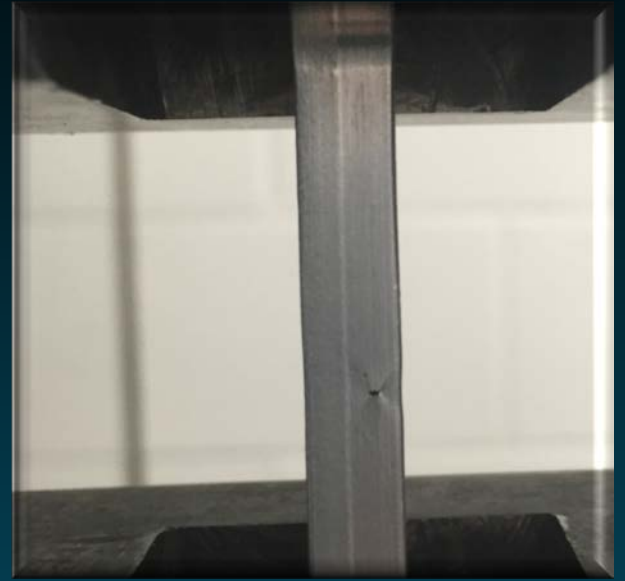
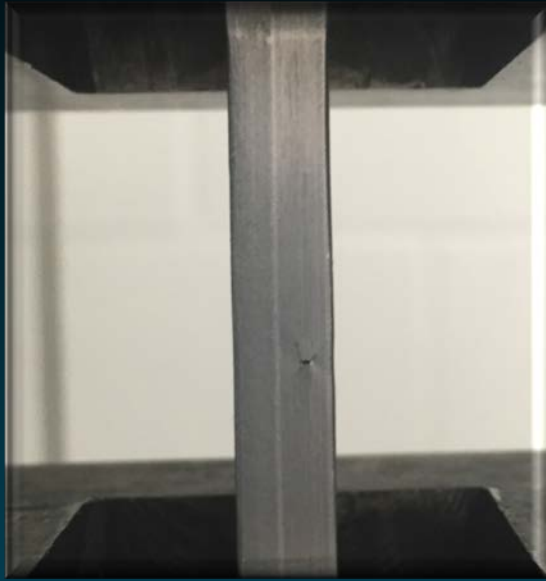
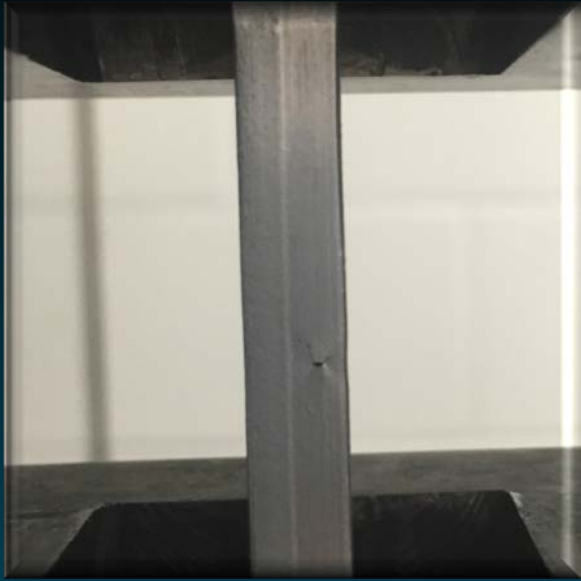
Tensile Results- Longitudinal Samples



Tensile Results- UAM Layers

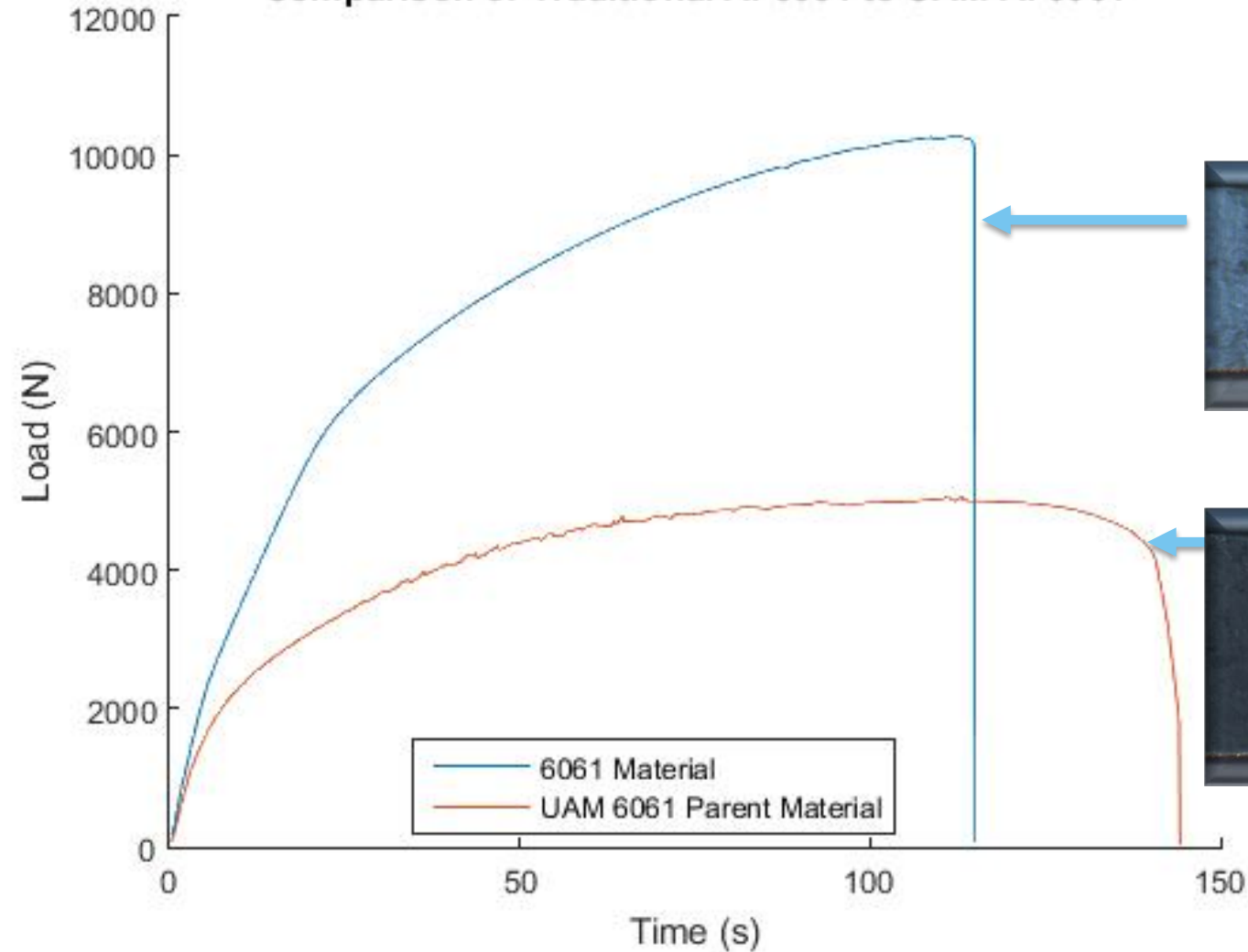


Tensile Results- Crack Initiation

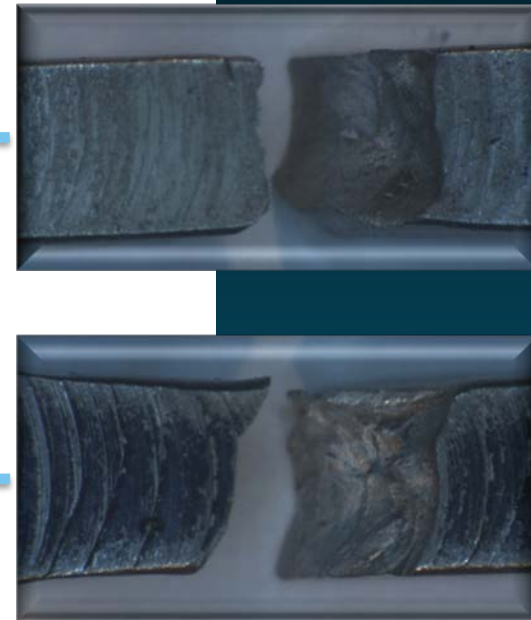
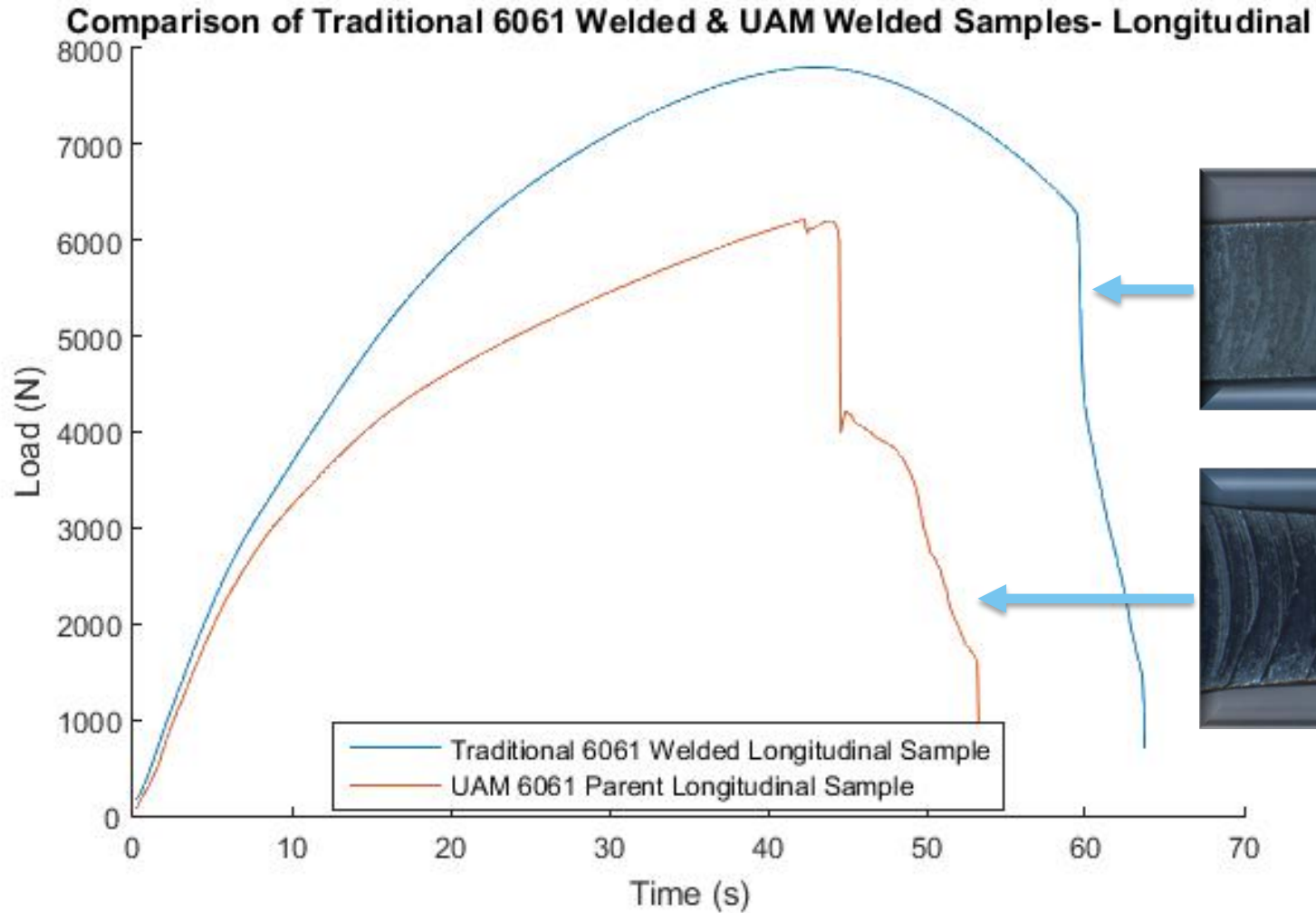


Tensile Results

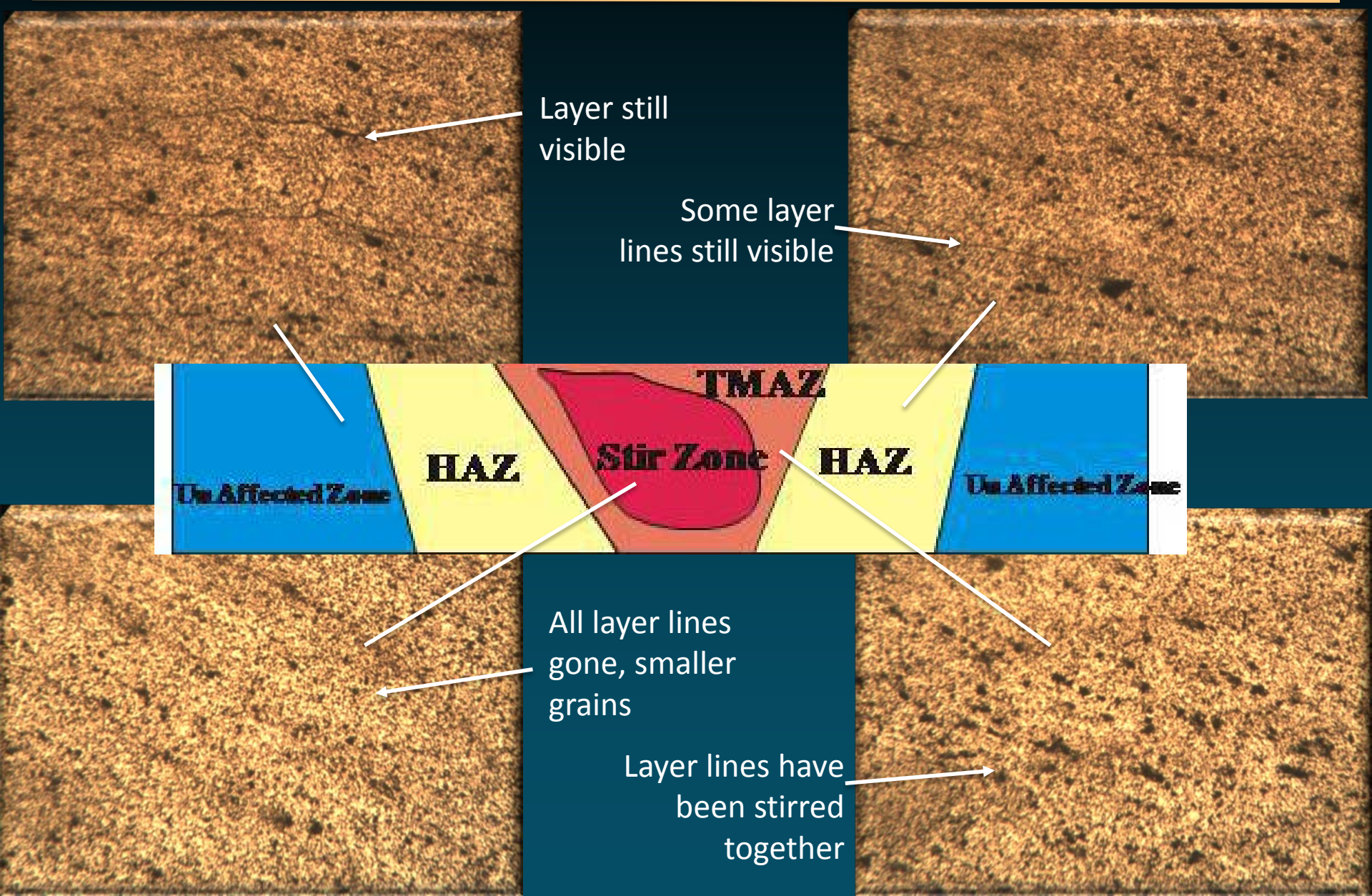
Comparison of Traditional AI 6061 to UAM AI 6061



Tensile Results



Friction Stir Welding: Ultrasonically Additively Manufactured Material



Conclusions

- Friction Stir Welding is an effective welding solution for Ultrasonic Additively Manufactured 6061
- Despite the inherent differences in base materials and heat treatments, tensile tests of longitudinal samples of UAM and conventionally manufactured Al 6061 T6 had very similar characteristics.
- Friction Stir Welding significantly enhances the material properties by stirring the layers, creating diffusion bonding, and reducing the grain size

Next Steps

- FSW UAM 6061 material to traditional 6061
- Optimize FSW process for EBF3 2219 material and determine the effects of post and pre weld heat treatment
- Optimize FSW process for DMLS AlSi10Mg and test
- Future potential research directions
 - evaluate the effect of material build orientation on joint properties
 - study welding of same alloy produced using different additive manufacturing techniques

Acknowledgements

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