Center for Advanced Non-Ferrous Structural Alloys
An Industry/University Cooperative Research Center

Project # 35:On the Influence of Microstructural Features of Linear Friction Welding and Electron Beam Additive Manufacturing Ti-6Al-4V on Tensile and Fatigue Mechanical Properties

Spring 2019 Semi-Annual Meeting
Iowa State University, Ames, IA
April 3-5, 2019

Student: Michael Mendoza (ISU)
Faculty: Peter Collins ISU
Industrial Mentors: Honeywell

Project 35: On the Influence of Microstructural Features of Linear Friction Welding and Electron Beam Additive Manufacturing Ti-6Al-4V on Tensile and Fatigue Mechanical Properties

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

- Student: Michael Mendoza (ISU)
- Advisor(s): Peter Collins (ISU)

Project Duration

PhD: January 2017 to July 2019

- **Problem:** Linear Friction Welding (LFW) offers cost reduction for aircraft structural components production. However, the information about its microstructure and mechanical properties is still limited.
- **Objective:** Characterize local microstructures (LFW) and their relationship with mechanical properties
- **Benefit:** The understanding of microstructure-properties relationship of LFW will improve manufacturing efficiency of aircraft components.

Recent Progress

- Larger EBSD characterization of The Welded Zone (WZ), WZ in-plane, Thermomechanical Affected Zone (TMAZ) and Parent Material (PM)
- Additional tensile tests and stress/strain curves on dogbone samples for the individual zones of LFW
- Preliminary ultrasonic fatigue test on Branson device for purchase and modifications
- PED-TEM data for dislocation density calculations

Metrics

Description	% Complete	Status
1. Literature review	95%	● (green)
2. Microstructure and tensile properties of dogbone samples within the individual three LFW zones	100%	● (green)
3. Conventional fatigue analysis (four-point bending test) of local microstructures EBAM-Ti-6Al-4V	80%	● (green)
4. Simulation and design (Comsol) of ultrasonic fatigue on local microstructures of EBAM-Ti-6Al-4V	95%	● (green)
5. Ultrasonic fatigue test design and modifications	20%	● (yellow)

Industrial Relevance

- The study of Ti-6Al-4V under different manufacturing processes is attracting more interest from industry because of cost reduction and potential improvements in mechanical properties.

- The main advantage of LFW resides in the fact that for aircraft structural components oversized ingots are machined to get the final component, so a large amount of material is wasted. LFW allows the use of not oversized ingots for welding them together to form the component with less use of initial material.

Linear Friction Welding (LFW)Ti-6Al-4V

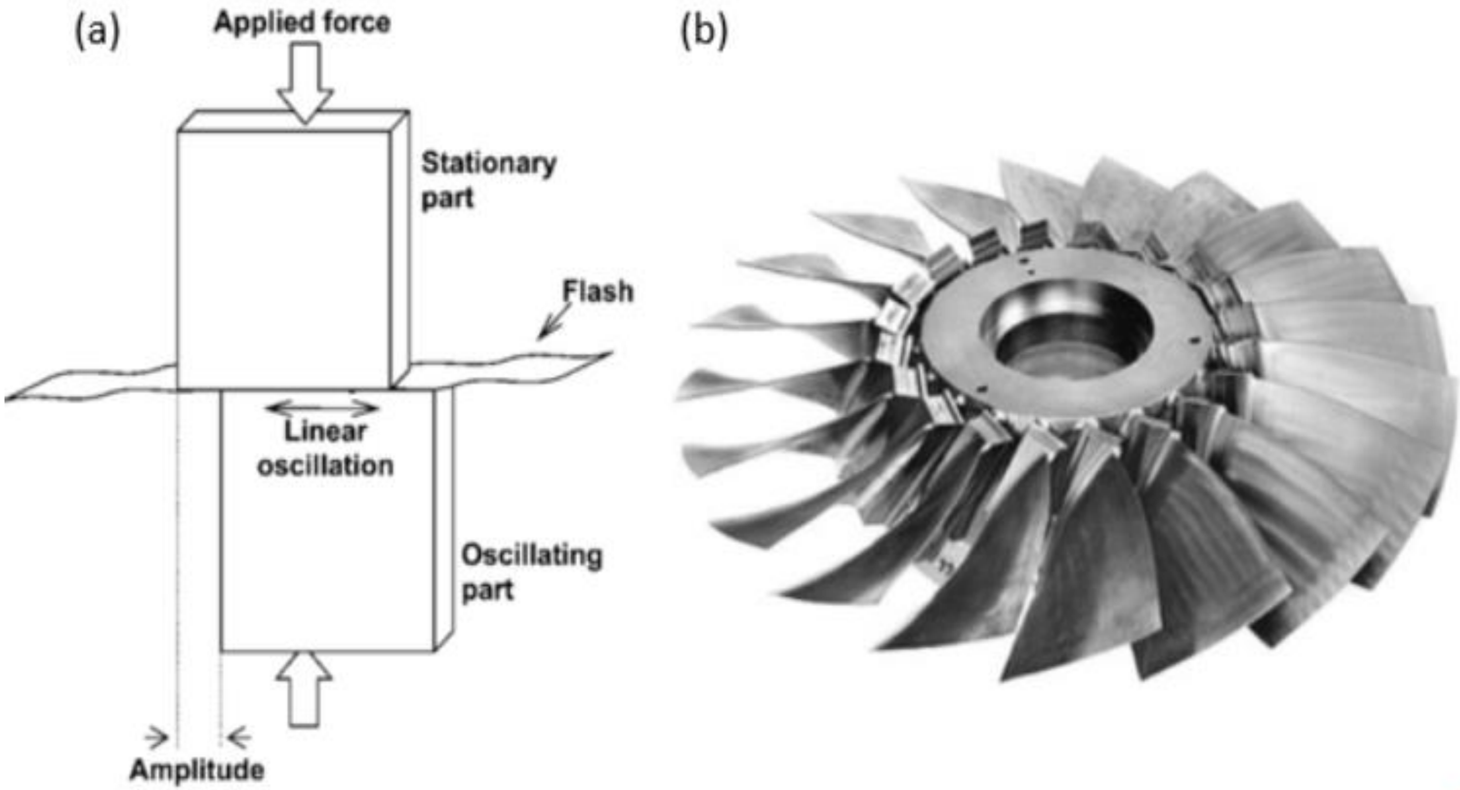
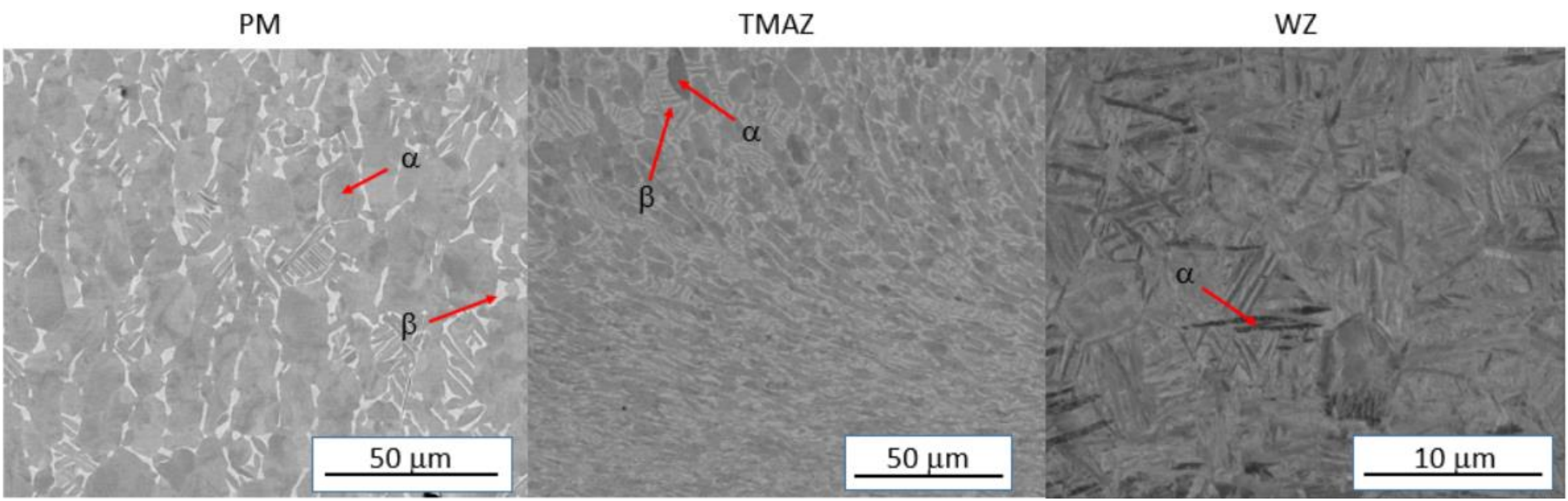


Figure 1.(a) Diagram of Linear Friction Welding process, (b) Integrated blisk (disc and blades)

Bhamji, I., Preuss, M., Threadgill, P. L., & Addison, A. C. (2011). Solid state joining of metals by linear friction welding: a literature review. *Materials science and technology, 27*(1), 2-12.

Linear Friction Welding (LFW) Zones



Backscatter electron micrographs on each zone

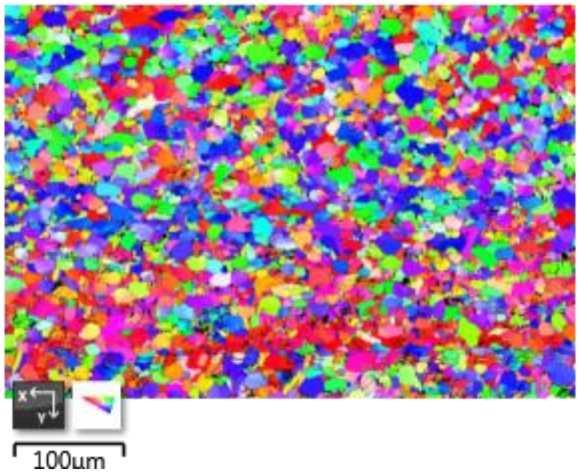
- PM - parent material with a bi-modal microstructure (i.e. primary α_p grains surrounded by α lamellar microstructure of α laths in a β matrix).
- TMAZ -Thermomechanical affected zone with a distorted bi-modal microstructure.
- WZ - Welded zone with a refined martensitic α' (needle like) laths in a β matrix.

Linear Friction Welding (LFW) Zones

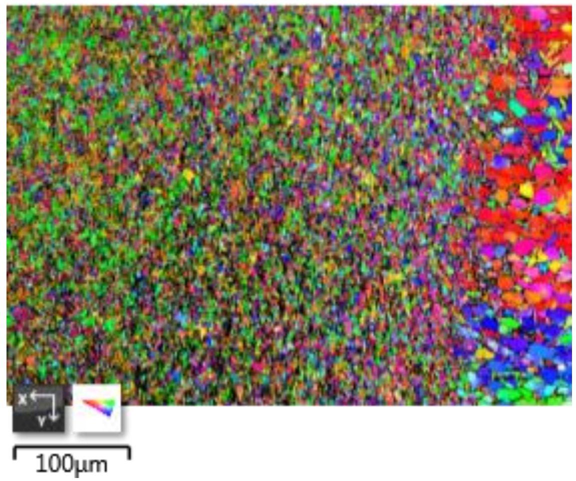
CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

IPF Z Color

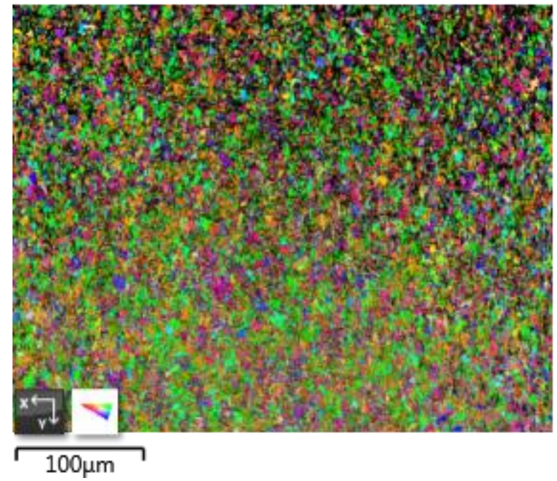
PM



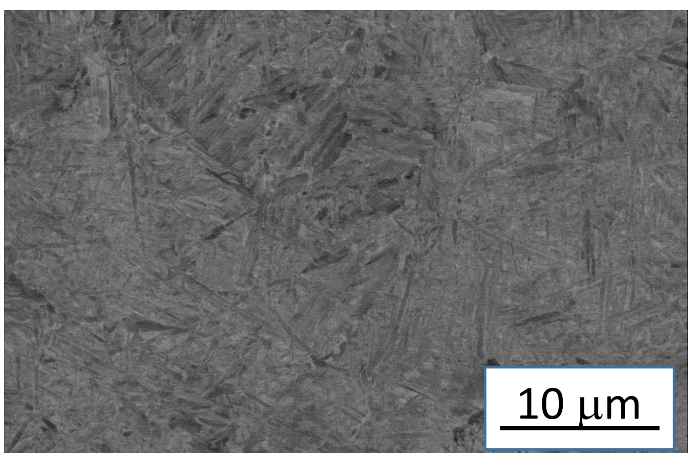
TMAZ



WZ

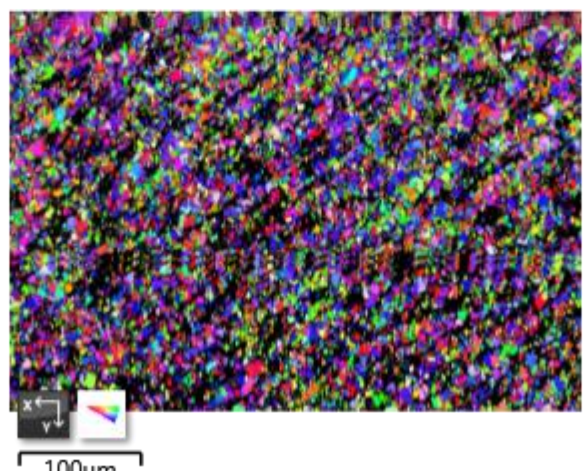


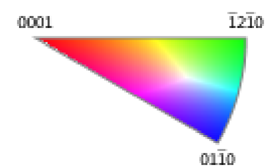
WZ in plane



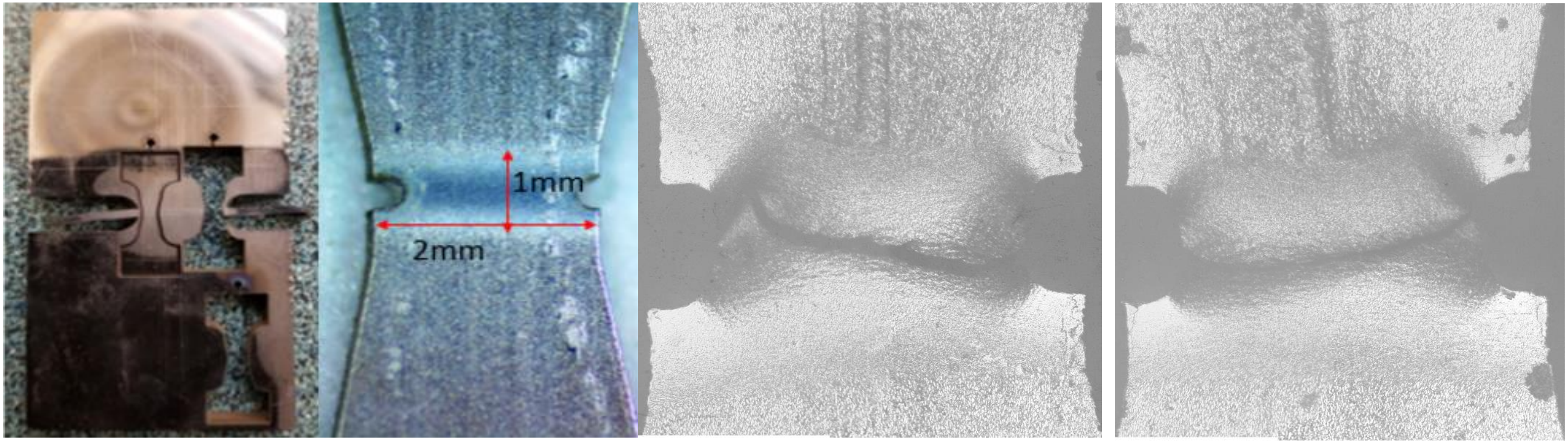
Backscatter electron micrograph

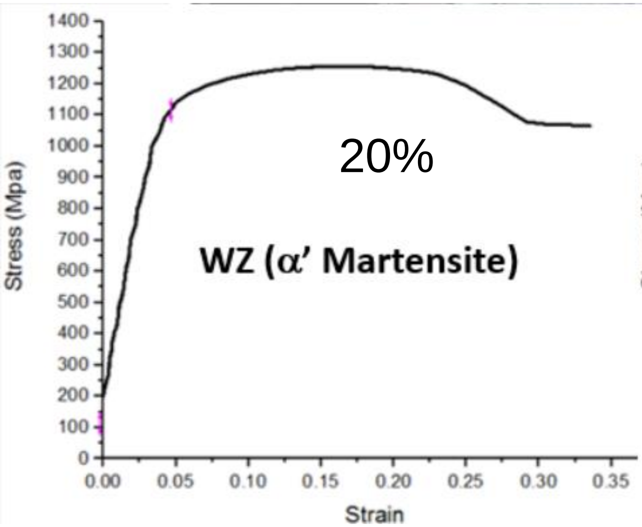
IPF Z Color 89

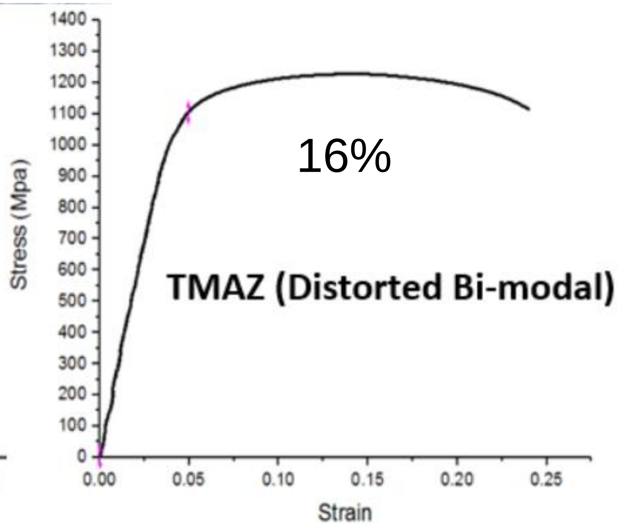


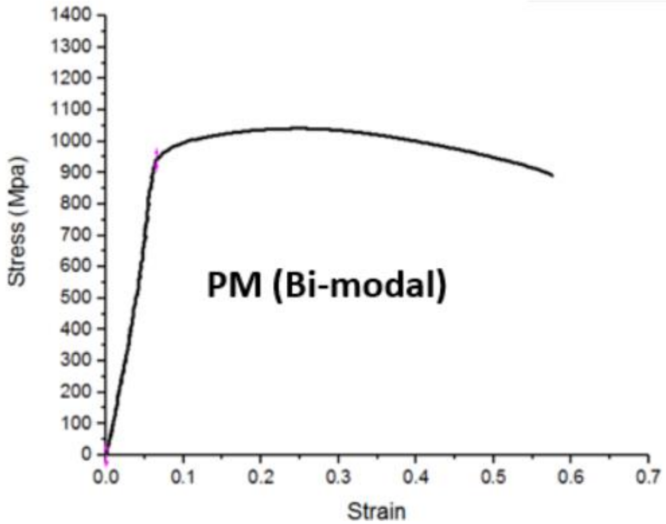


Current Progress on Tensile Properties of LFW-Ti-6Al-4V

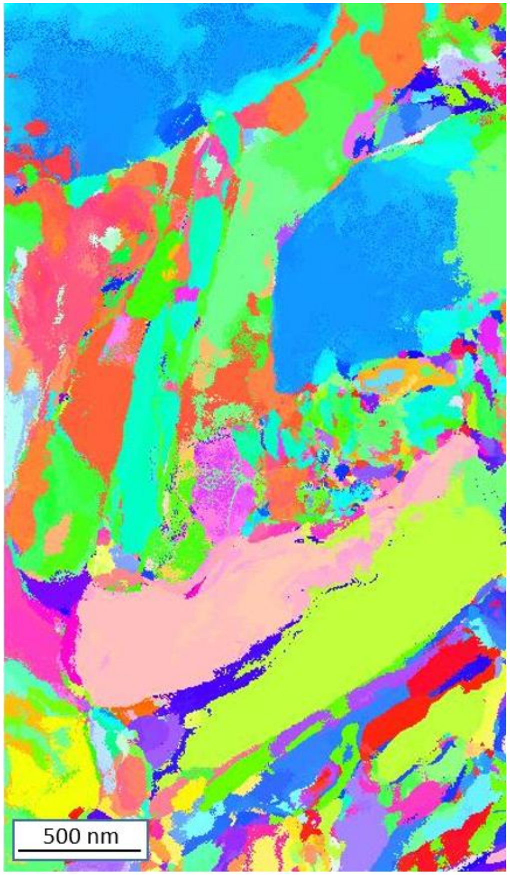




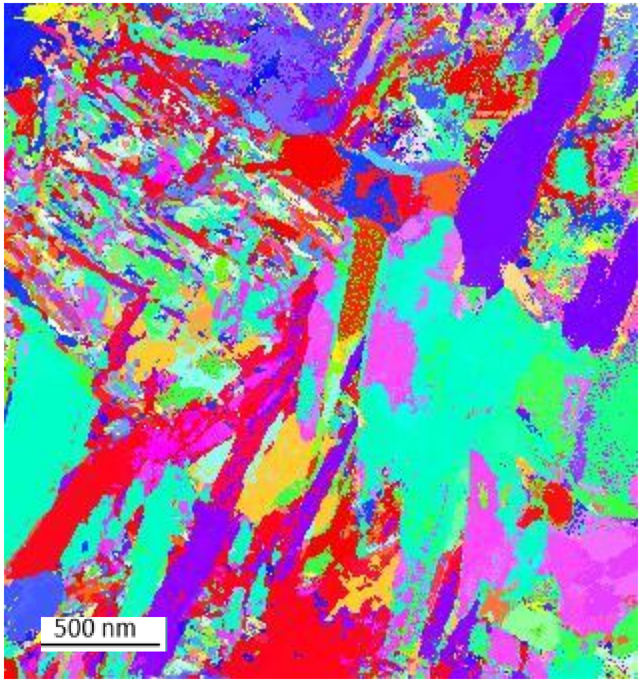




Dislocation Density Analysis



PED-TEM orientation data of WZ for dislocation density analysis

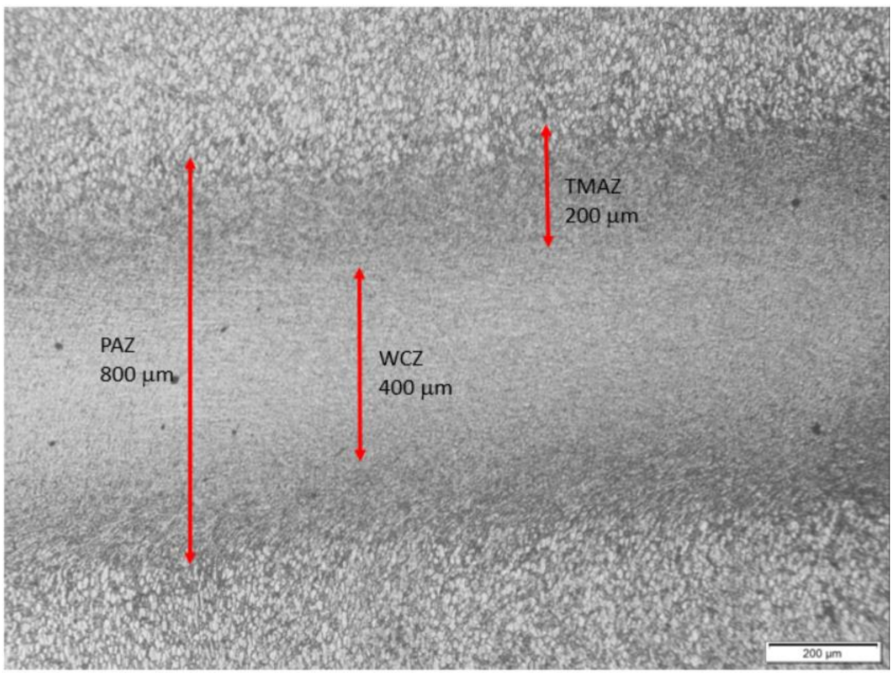


PED-TEM orientation data of TMAZ for dislocation density analysis

Orientation information is the input file for the MATLAB code for dislocation density calculation

Fatigue Approach

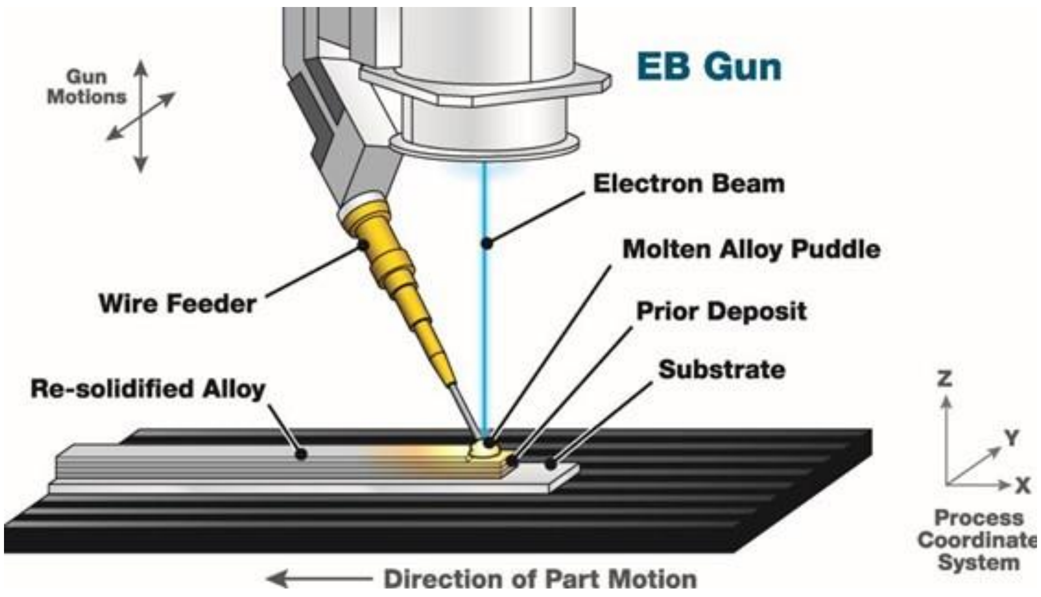
Tensile properties are important, but fatigue analysis is also necessary due to the presence of cyclic stresses on Ti-6Al-4V aircraft components.



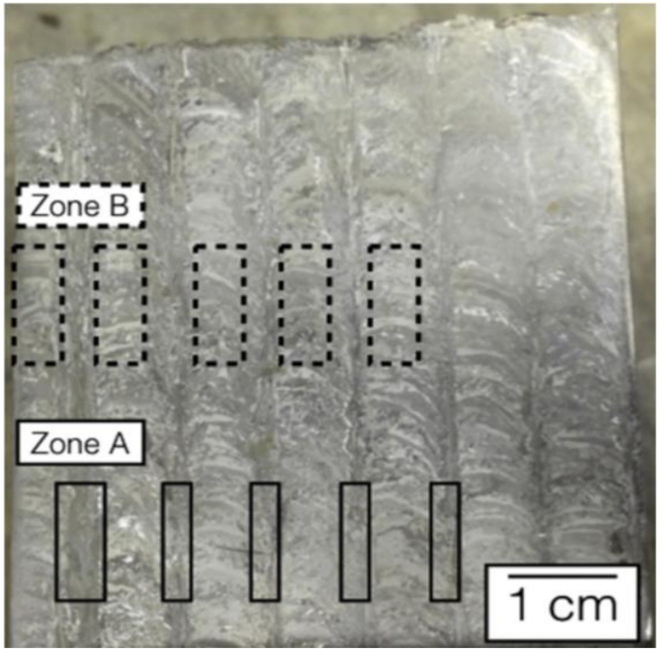
LFW-Ti-6Al-4V

EBAM-Ti-6Al-4V

Electron Beam Additive Manufacturing (EBAM)



http://www.sciaky.com/additive-manufacturing/wire-am-vs-powder-am



- Electron beam as a heat source
- Ti-6Al-4V wire as a feedstock
- Vacuum chamber that also protects the alloy

- Two distinct zones can be recognized on this picture, zone A comprises vertically elongated prior β grains with very little variation in α lath thickness and zone B with a pronounce variation in α lath thickness and a more scattered orientation.

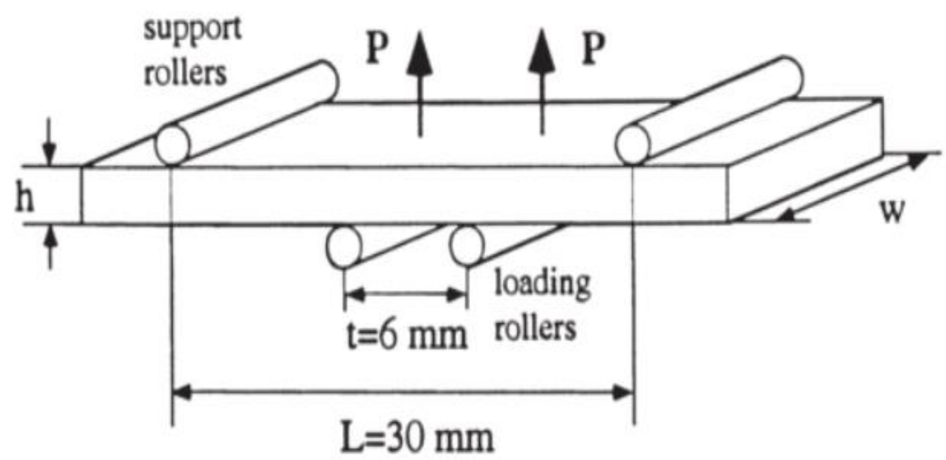
Hayes, B. J., et al. (2017). "Predicting tensile properties of Ti-6Al-4V produced via directed energy deposition." Acta Materialia **133**: 120-133.

Conventional Fatigue Analysis on EBAM-Ti-6Al-4V

Four-point bending test is selected as a convenient method for fatigue studies due to several reasons:

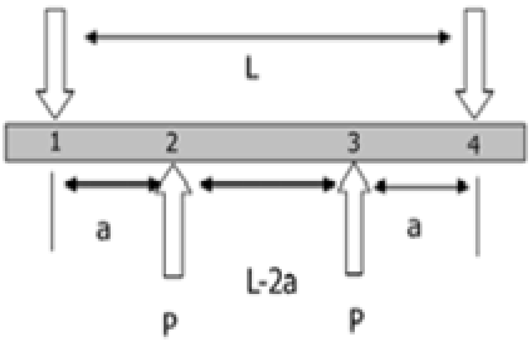
- It produces a uniform maximum stress on the surface.
- Easy sample mounting and dismounting as no special gripping is required.
- It is also suitable to evaluate specific microstructures from small samples.

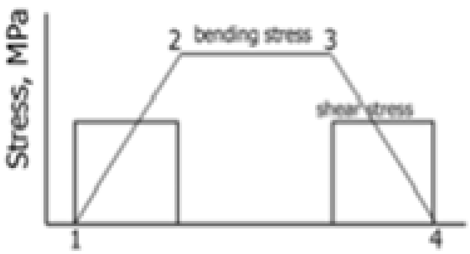
20 specimens total (Length: 40 mm, width: 5 mm, Thickness: 4.5 mm) 10 for zone **A** and 10 for zone **B** were sectioned via EDM with the suitable dimensions for capturing the interested microstructure and construct the respective *S-N* curve and fracture analysis.



T. Zhai, Y. Xu, J. Martin, A. Wilkinson, G. Briggs, A self-aligning four-point bend testing rig and sample geometry effect in four-point bend fatigue, International Journal of Fatigue 21(9) (1999) 889-894.

Four-Point Bending Test





Optimum testing geometry for uniform stress distribution consistent with the value calculated by the beam theory.

t = load span
L = support span
h = thickness

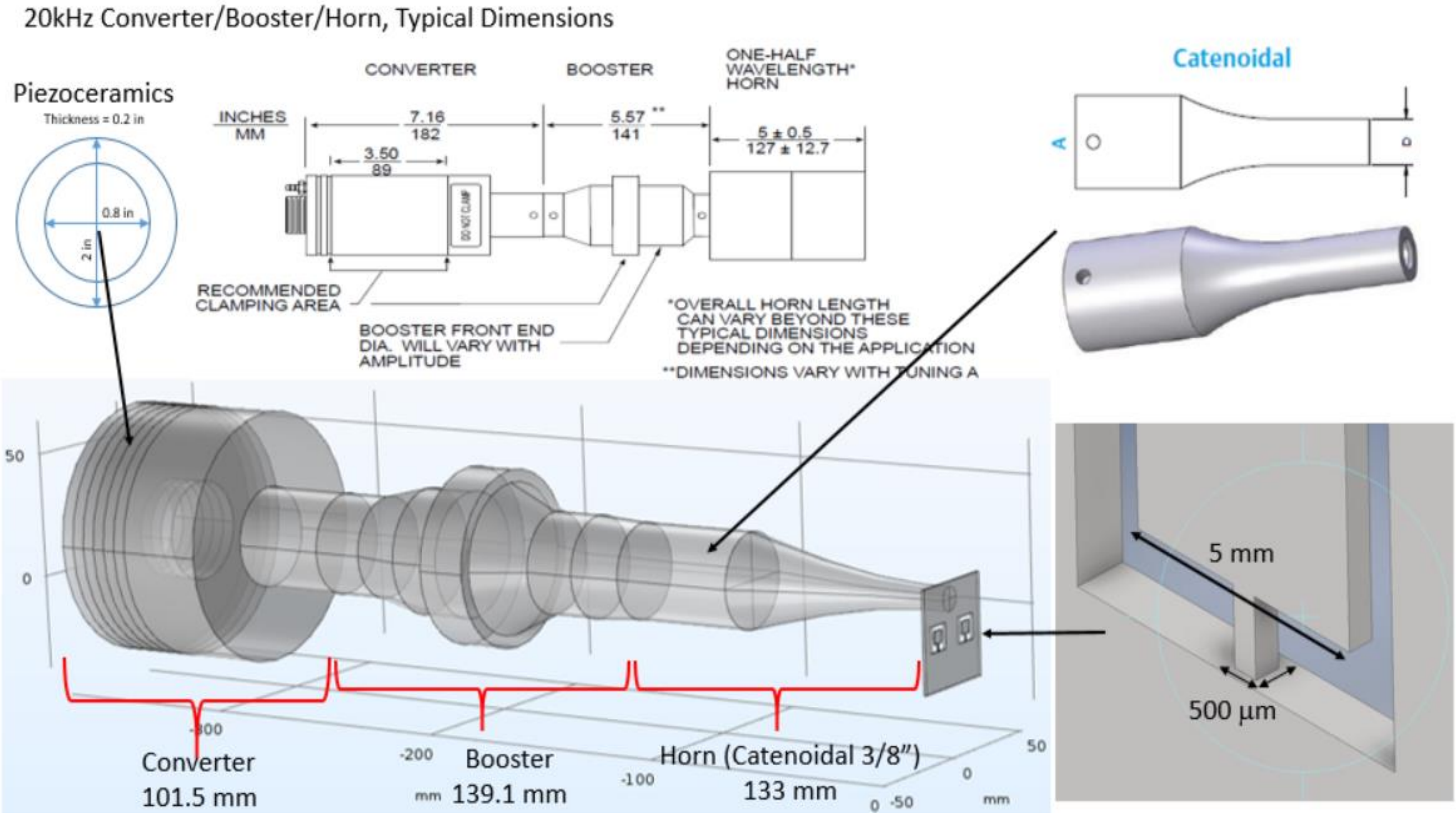
$$t/h = (5.74\ mm)/(4.5\ mm) = 1.27$$
$$L/t = (23\ mm)/(5.74\ mm) = 4.0$$

Pilchak, A. L. (2009). The effect of friction stir processing on the microstructure, mechanical properties and fracture behavior of investment cast Ti-6Al-4V, The Ohio State University.

T. Zhai, Y. Xu, J. Martin, A. Wilkinson, G. Briggs, A self-aligning four-point bend testing rig and sample geometry effect in four-point bend fatigue, International Journal of Fatigue 21(9) (1999) 889-894.

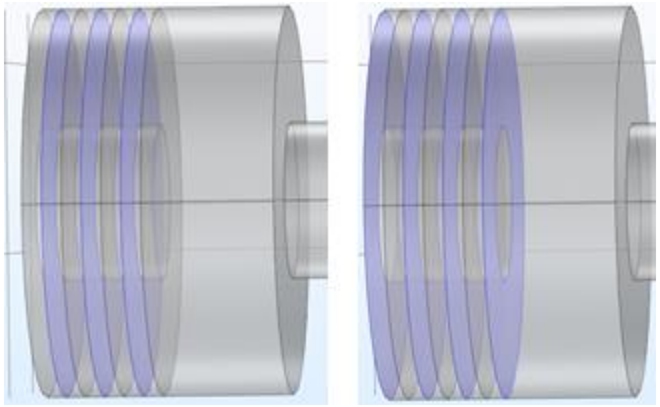
Comsol Model of Ultrasonic Fatigue on EBAM-Ti-6Al-4V

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS



Branson Ultrasonics Corporation.

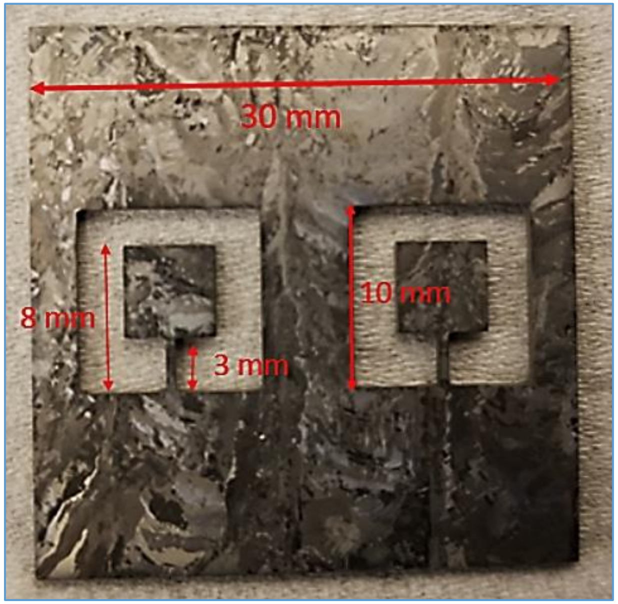
Resonance system



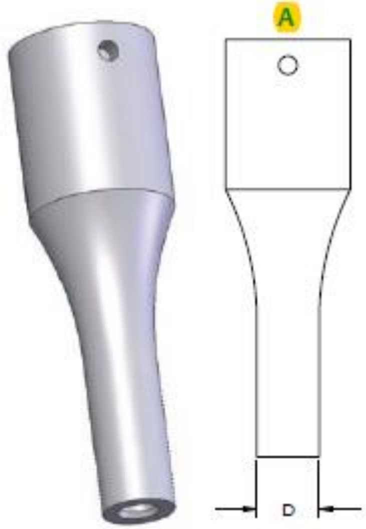
Electric potential (V)   Ground

6 piezoceramic discs, stacked mechanically in series and electrically in parallel.

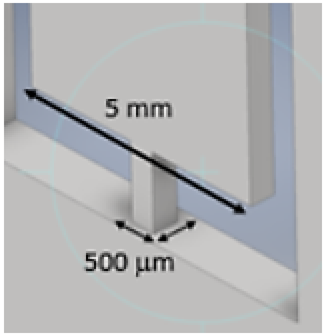
Gold 1:1.5
101-149-057
Booster for 20kHz



Catenoidal Horn

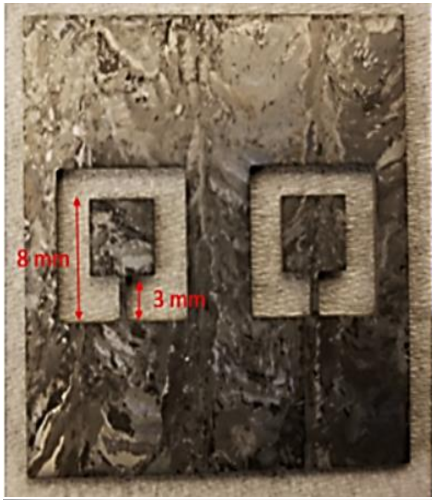


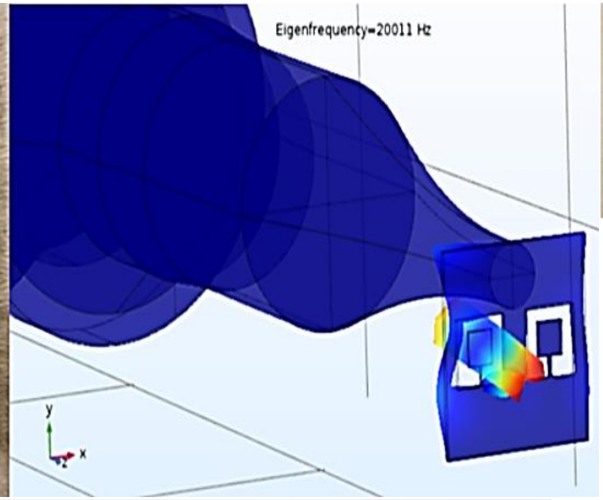
608-001-021

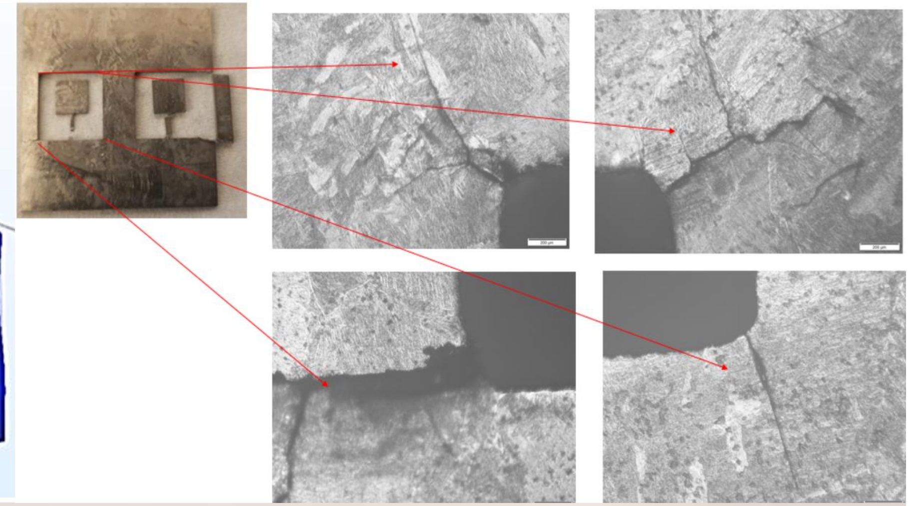


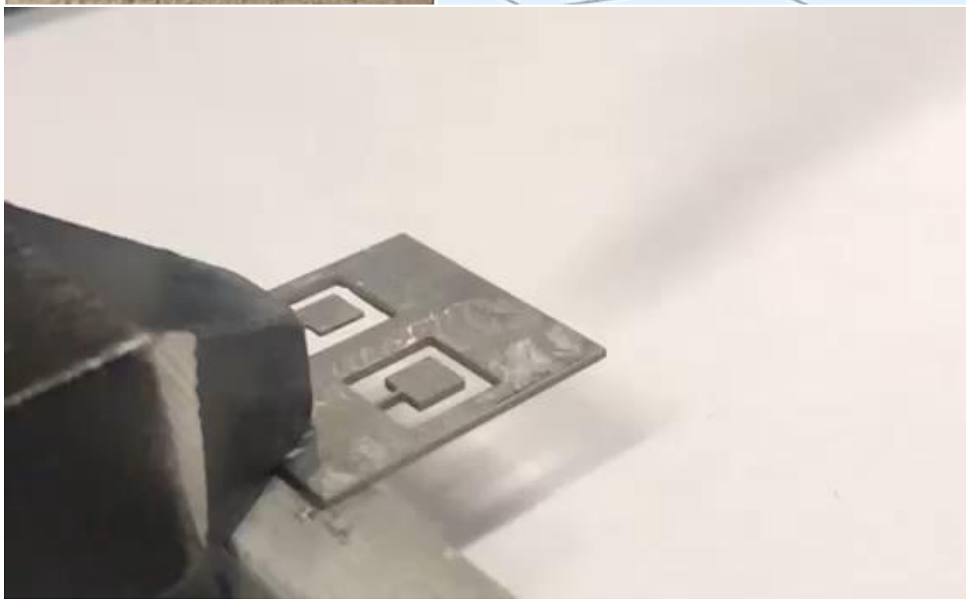
Sample dimensions

Ultrasonic Fatigue Prediction and Test on EBAM-Ti-6Al-4V

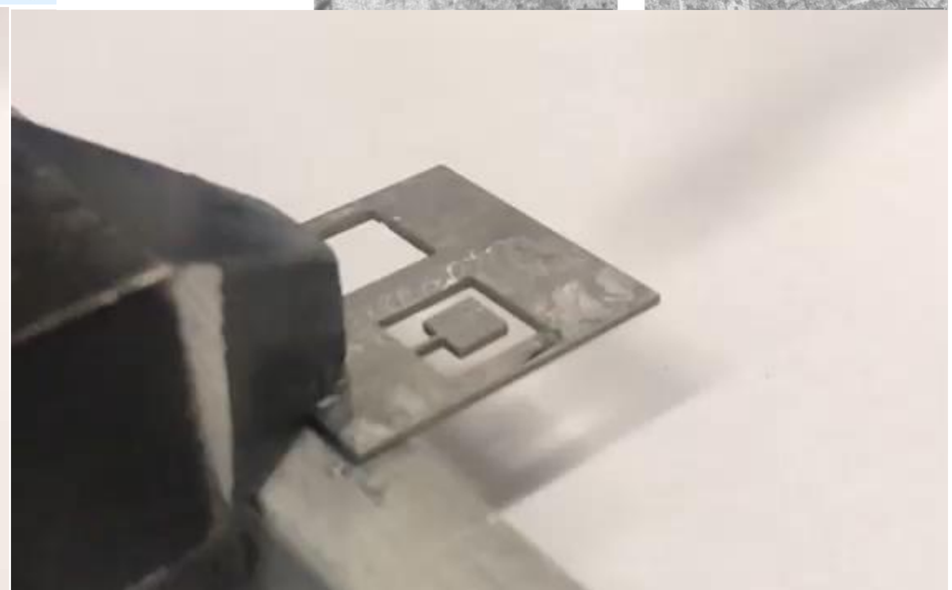








Right thickness

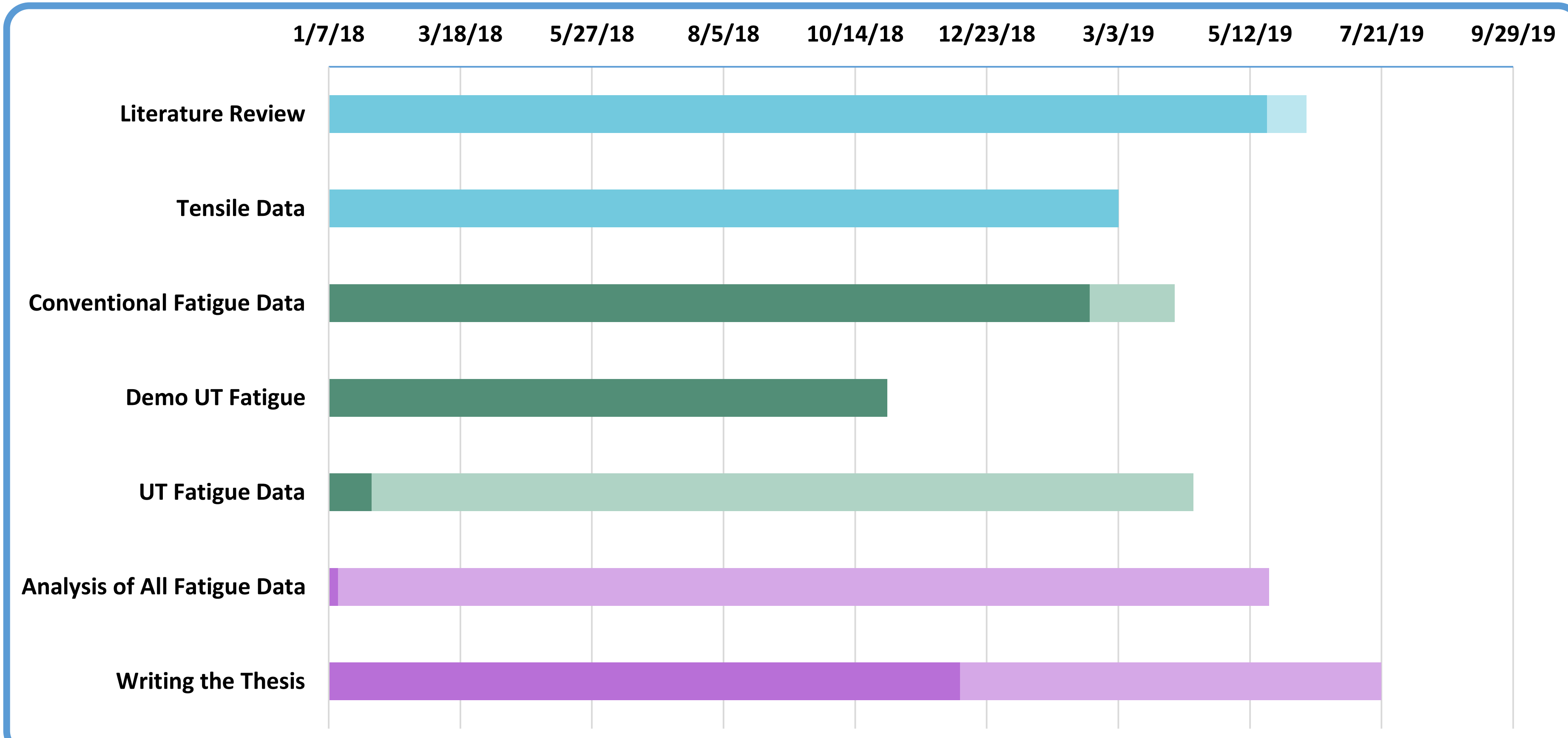


Wrong thickness

Summary of Pending Work

- TEM-PED data and MATLAB code for dislocation density calculations
- S-N curve construction and analysis from conventional fatigue test
- Branson Ultrasonic equipment modifications
- S-N curve construction and analysis from ultrasonic fatigue test
- Analysis and comparison of the fatigue tests

Progress Gantt Chart



The authors acknowledge the support of the Center for Advanced Non-Ferrous Structural Alloys (CANFSA), an NSF Industry/University Cooperative Research Center (I/UCRC) between Iowa State University and The Colorado School of Mines.

The authors also acknowledge the support of the Defense Advanced Research Projects Agency (DARPA)

Thank you very much!

Michael Mendoza

mym@iastate.edu

CANFSA

Center for Advanced Non-Ferrous Structural Alloys

An Industry/University Cooperative Research Center

Project 35 - On the Influence of Microstructural Features of Linear Friction Welding and Electron Beam Additive Manufacturing Ti-6Al-4V on Tensile and Fatigue Mechanical Properties

Student: *Michael Mendoza*

Faculty: *Peter Collins*

Industrial Partners: *Honeywell*

Project Duration: *January. 2017 – July 2019*

Achievement

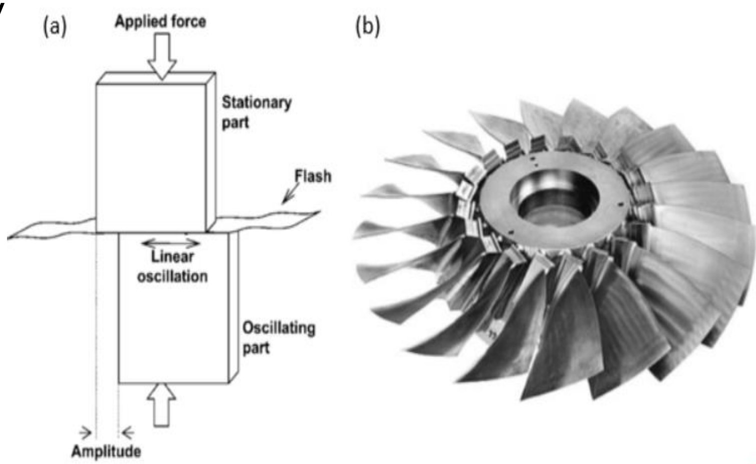
- Characterize local microstructures of Linear Friction Welding (LFW) and their relationship with mechanical properties.

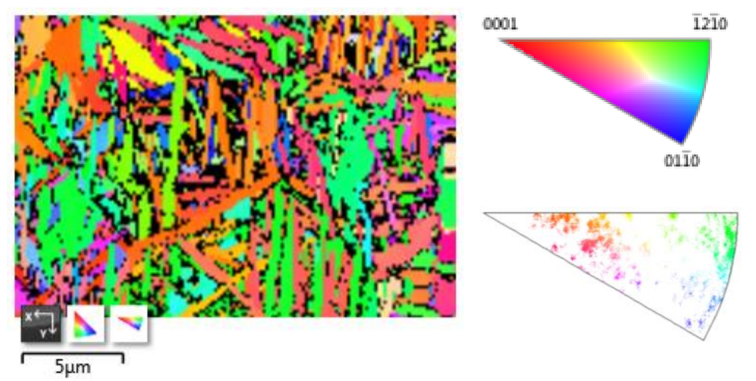
Significance and Impact

- New welding methods as LFW offers cost reduction for aircraft structural components production. Understanding the microstructure-properties relationship in the process is a key factor to its implementation.

Research Details

- Microstructure characterization of individual LFW-Ti-6Al-4V zones to evaluate tensile properties and exploration of fatigue analysis on larger local microstructures as EBAM-Ti-6Al-4V for future applicability on LFW.





Center Proprietary – Terms of CANFSA Membership Agreement Apply

Project 35 - Characterization of Microstructures and Mechanical Properties in LFW Ti-6Al-4V

Student: *Michael Mendoza*

Faculty: Peter Collins

Industrial Partners: *Honeywell*

Project Duration: *January 2017 – July 2019*

Achievement

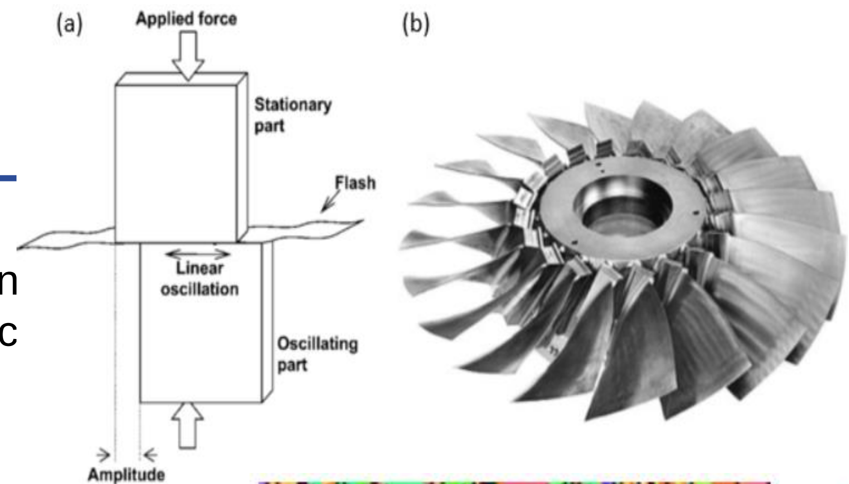
- Characterize local microstructures of Linear Friction Welding (LFW) and their relationship with mechanic properties

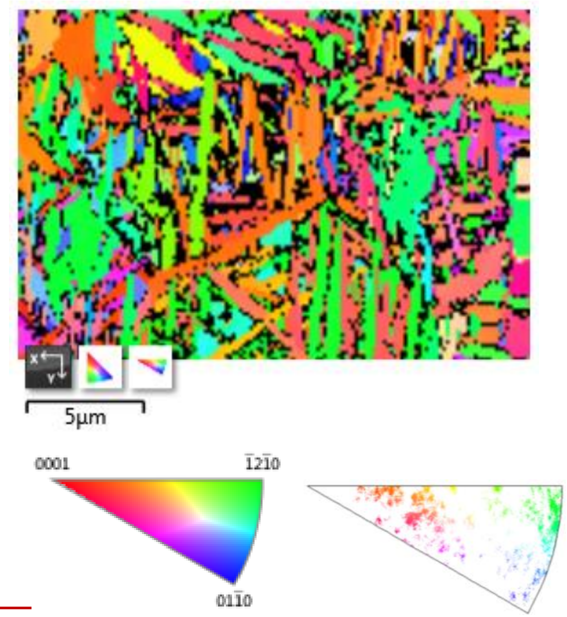
Significance and Impact

- New welding methods as LFW offers cost reduction for aircraft structural components production. Understanding the microstructure-properties relationship in the process is a key factor to its implementation.

Research Details

- Microstructure characterization of individual LFW-Ti-6Al-4V zones to evaluate tensile properties and exploration of fatigue analysis on larger local microstructures as EBAM-Ti-6Al-4V for future applicability on LFW.





Project 35 - Characterization of Microstructures and Mechanical Properties in LFW Ti-6Al-4V

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

Student: *Michael Mendoza*

Faculty: *Peter Collins*

Industrial Partners: *Honeywell*

Project Duration: *January. 2017 – July 2019*

Program Goal

- Characterize the microstructure and mechanical properties of Linear Friction Welding (LFW)

Approach

- Evaluate tensile properties on LFW-Ti-6Al-4V and explore fatigue analysis on larger microstructures as EBAM-Ti-6Al-4V for future applicability on LFW.

Benefits

- The understanding of microstructure-properties relationship of LFW will improve manufacturing efficiency of aircraft components.