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

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

Fall 2018 Semi-Annual Meeting
Colorado School of Mines, Golden, CO
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Student: Michael Mendoza (ISU)

Faculty: Peter Collins ISU

Industrial Mentors: Honeywell

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IOWA STATE UNIVERSITY

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

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

Project Duration
PhD: January 2017 to May 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
- Optical, SEM and EBSD characterization of The Welded Zone (WZ), Thermomechanical Affected Zone (TMAZ) and Parent Material (PM)
- Tensile tests and stress/strain curves on dogbone samples for the individual zones of LFW
- Exploration of fatigue analysis on bigger local microstructures as EBAM-Ti-6Al-4V for future applicability on the small local microstructures of LFW

Metrics

Description	% Complete	Status
1. Literature review	90%	● (green)
2. Microstructure and tensile properties of dogbone samples within the individual three LFW zones	90%	● (green)
3. Conventional fatigue analysis (four-point bending test) of local microstructures EBAM-Ti-6Al-4V	40%	● (green)
4. Simulation and design (Comsol) of ultrasonic fatigue on local microstructures of EBAM-Ti-6Al-4V	90%	● (green)
5. Ultrasonic fatigue analysis and comparison with conventional fatigue results	0%	● (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

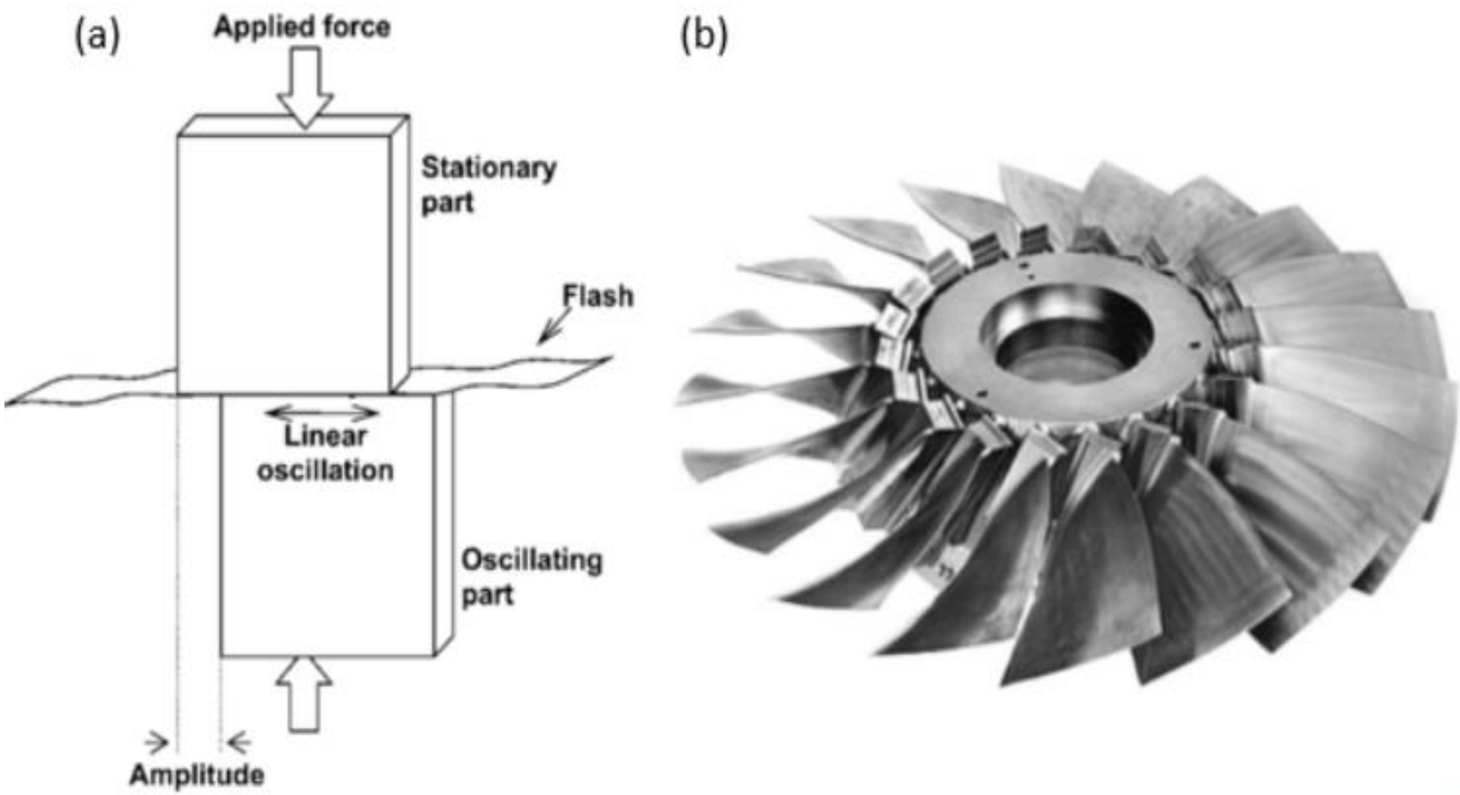
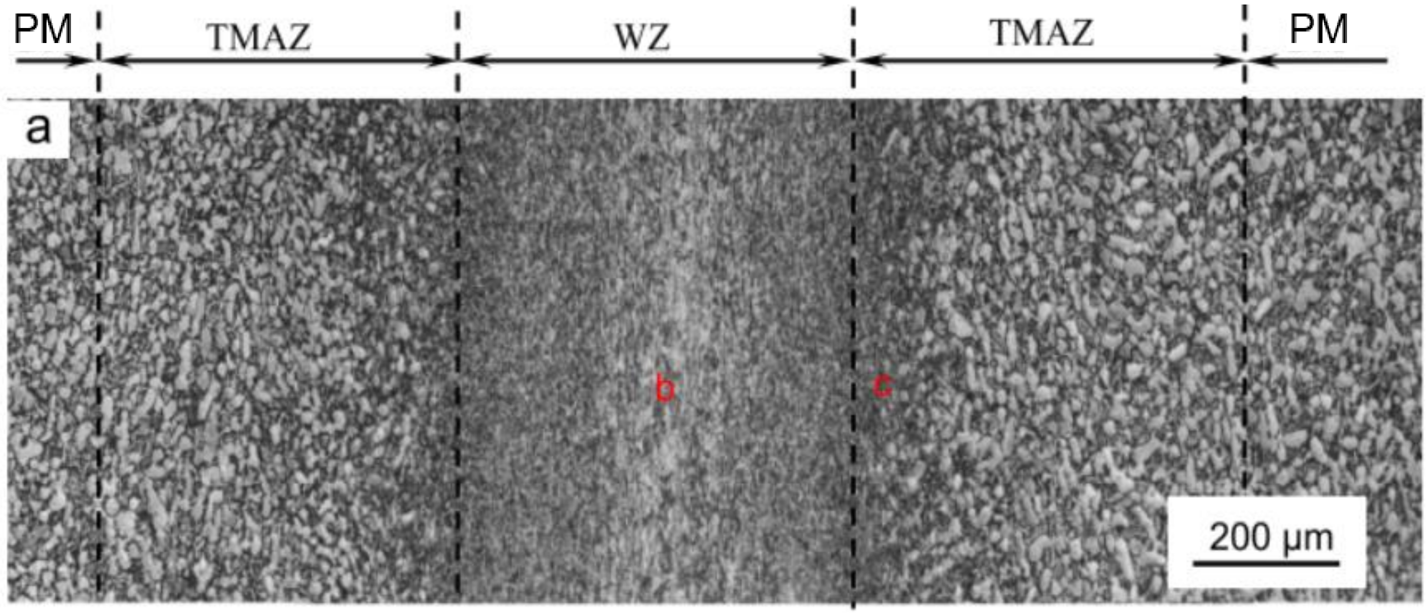


Figure 1.(a) Diagram of Linear Friction Welding process, (b) Integrated blisk (disc and blades)

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.

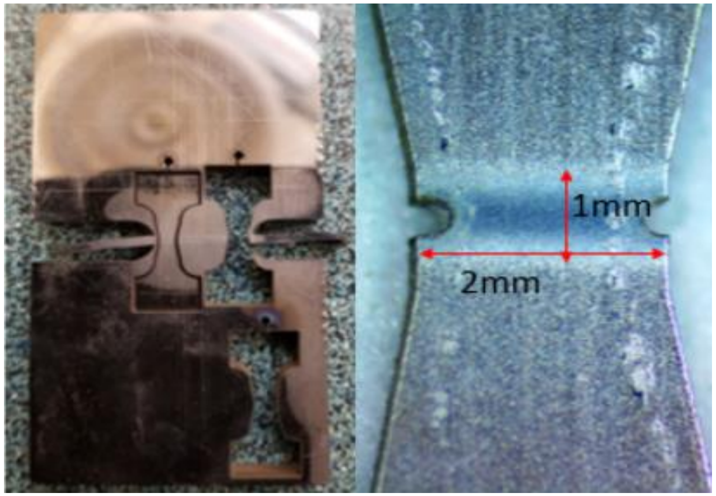
Linear Friction Welding (LFW) Zones



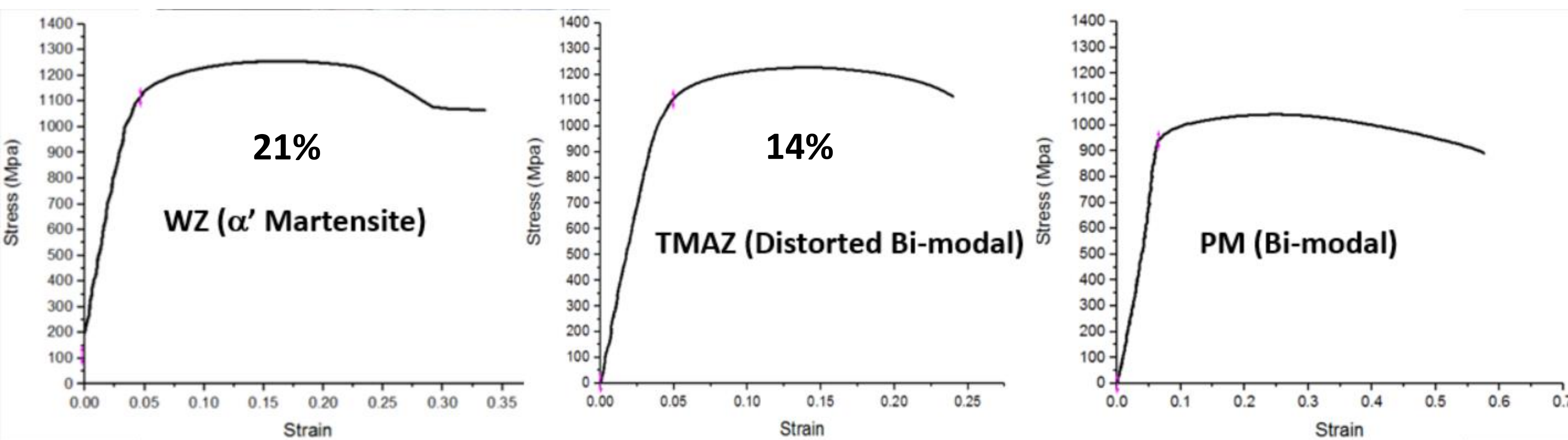
Wen, G., Ma, T., Li, W., Li, J., Guo, H., & Chen, D. (2014). Cyclic deformation behavior of linear friction welded Ti6Al4V joints. *Materials Science and Engineering: A, 597*, 408-414.

- 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) or Widmanstätten microstructure depending on the cooling rate.

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



	$Y_{0.2\%\,(Mpa)}$	$U_{TS\,(Mpa)}$	$R_{S\,(Mpa)}$	%El	$Y_{HV\,(Mpa)}$
WZ	1159	1256	1065	33.52	1324
TMAZ	1088	1128	1115	24.00	1196
PM	955	1041	890	57.55	1098



Texture on Welded Zone (WZ)

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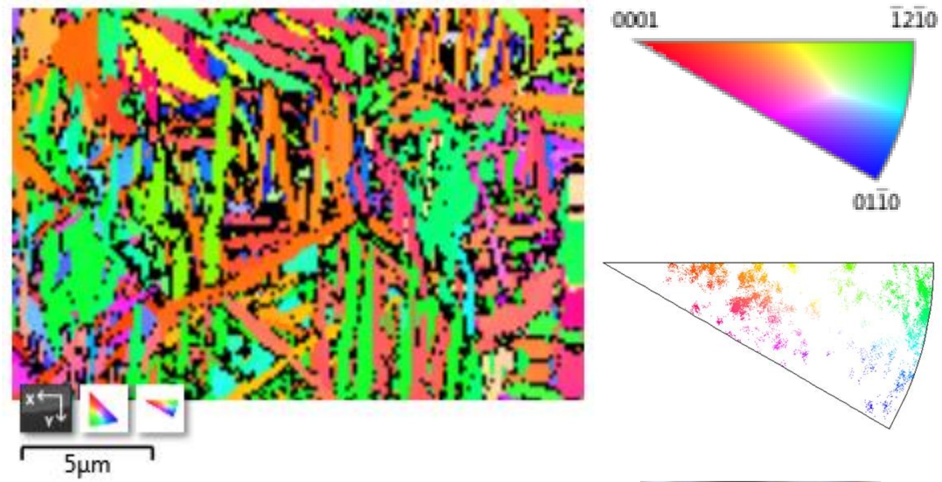
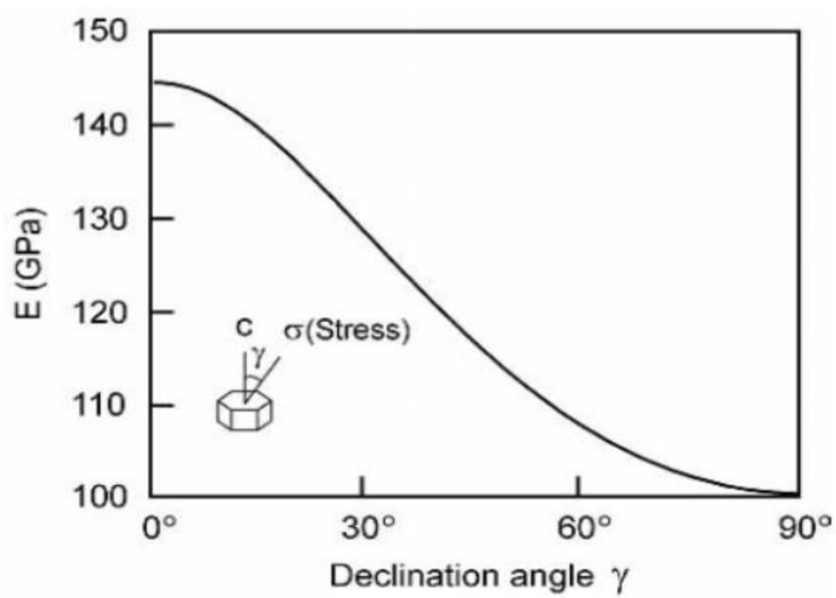
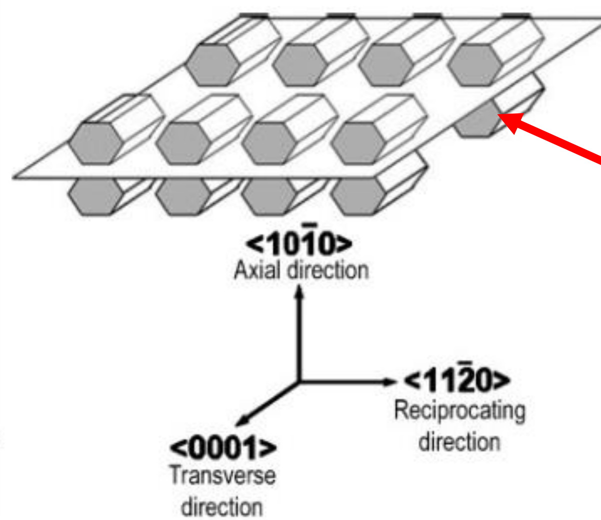
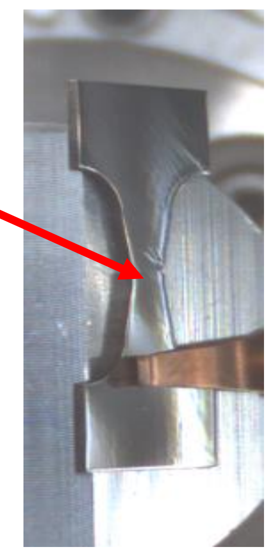
- For the LFW-Ti-6Al-4V specimen, we expect to confirm via TEM the identification of the α' titanium phase in the WZ to compare it with the one commonly observed in LENS-Ti-6AL-4V processes ($Y_{0.2\%}$= 10% greater than PM).
- We expect to see a strong transverse texture.







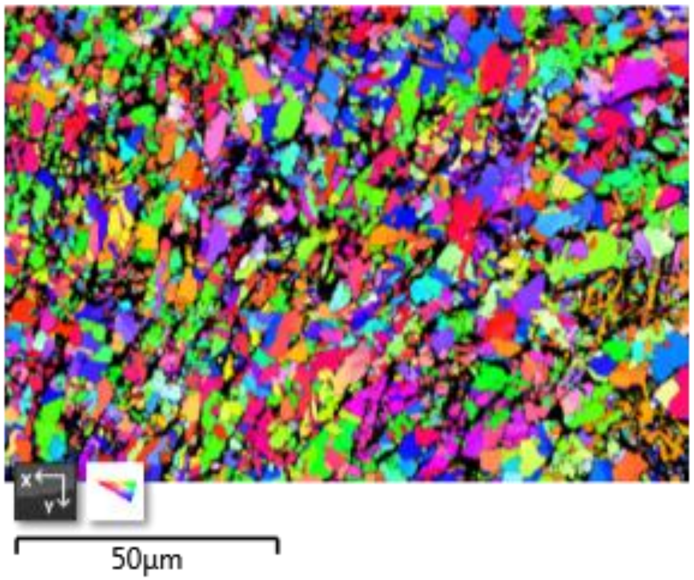


Lütjering, G. and J. C. Williams (2007). Titanium, Springer.

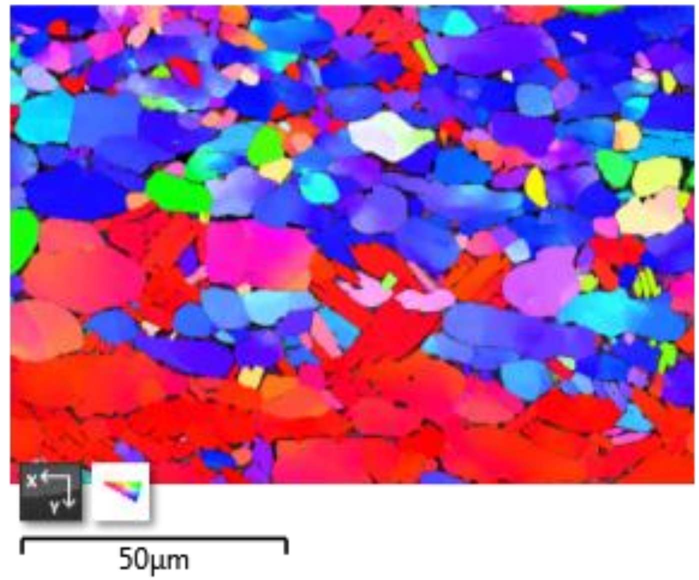
Karadge, M., et al. (2007). "Texture development in Ti–6Al–4V linear friction welds." Materials Science and Engineering: A **459**(1-2): 182-191.

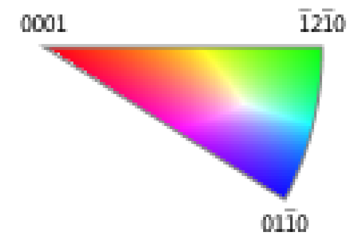
Texture on Thermomechanical-Affected and Parent Material Zones

TMAZ



PM





- The TMAZ zone shows a very random orientation, and the PM shows a certain texture in the <0001> direction. Larger maps have to be acquired to capture better statistics.

Fatigue Approach

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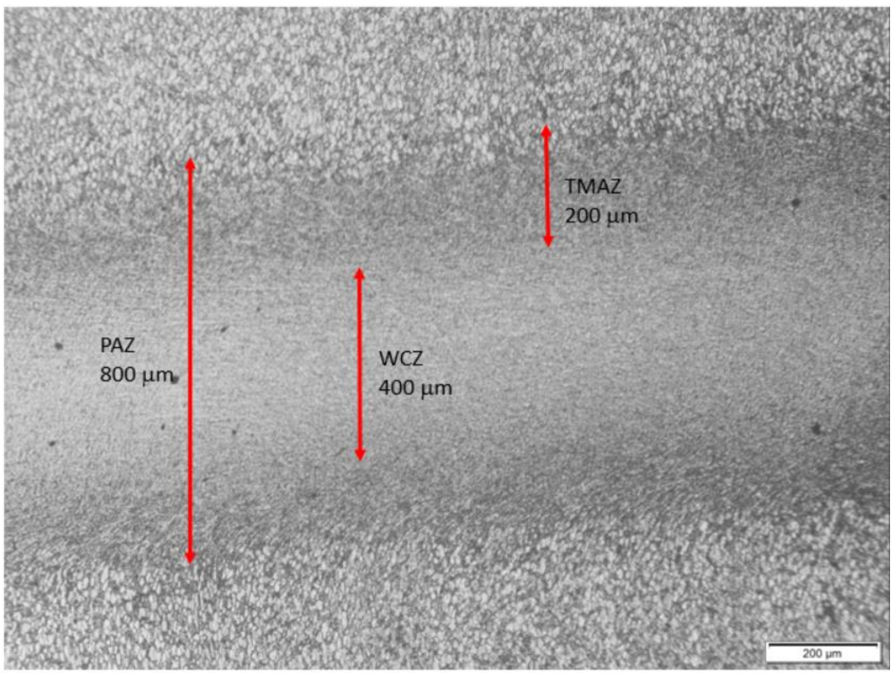
Tensile properties are important, but fatigue analysis is also necessary due to the presence of cyclic stresses on Ti-6Al-4V aircraft components.



LFW-Ti-6Al-4V

EBAM-Ti-6Al-4V

Electron Beam Additive Manufacturing (EBAM)

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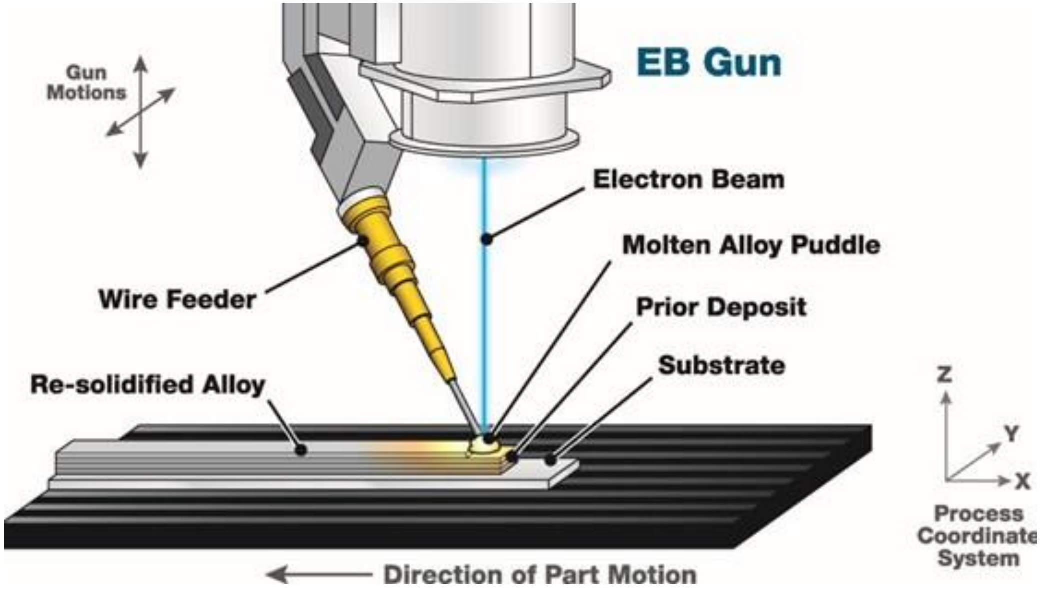
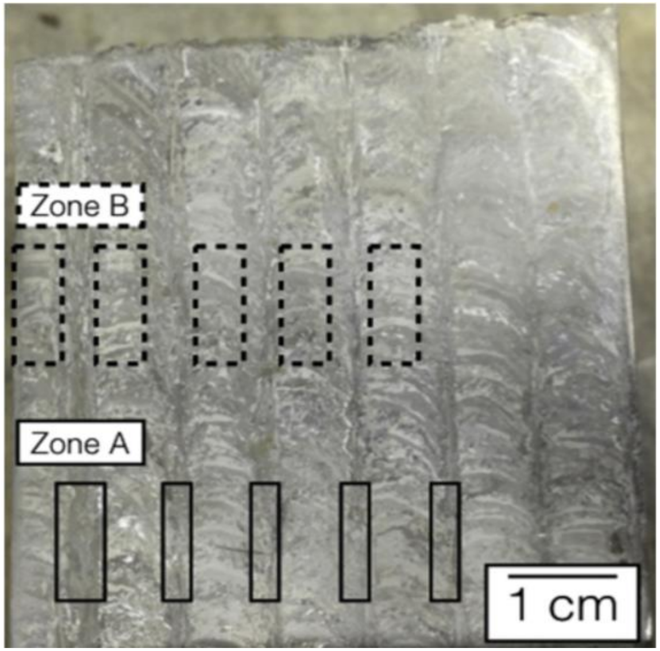


http://www.sciaky.com/additive-manufacturing/wire-am-vs-powder-am

- 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

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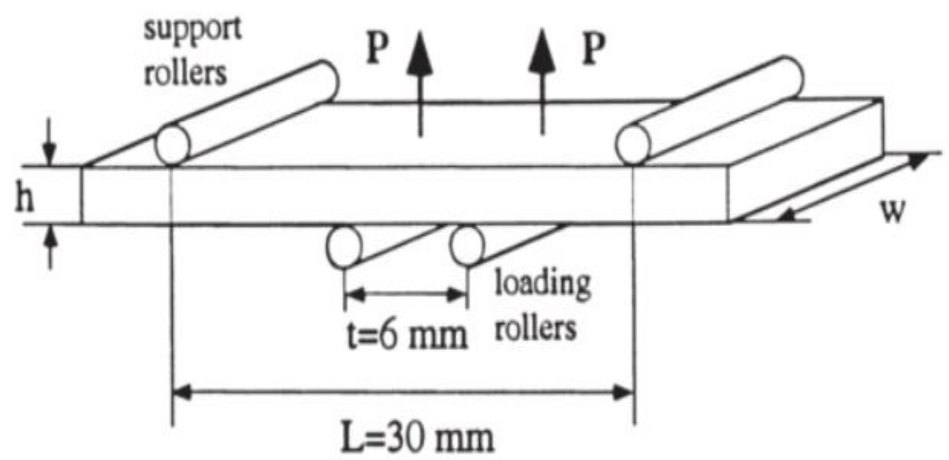
Four-point bending test is selected as a convenient method for fatigue studies due to several reasons:

- 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

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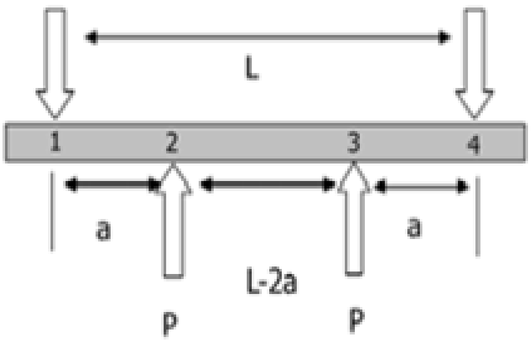

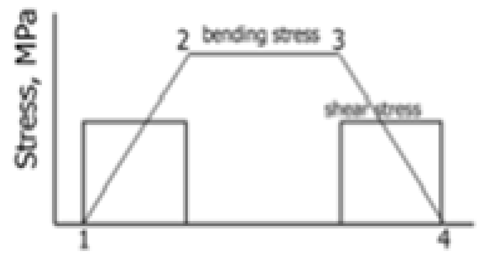

Optimum testing geometry for uniform stress distribution consistent with the value calculated by the beam theory.

t = load span
L = support span
h = thickness

t/h = 1.2-1.5
L/t = 4-5

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

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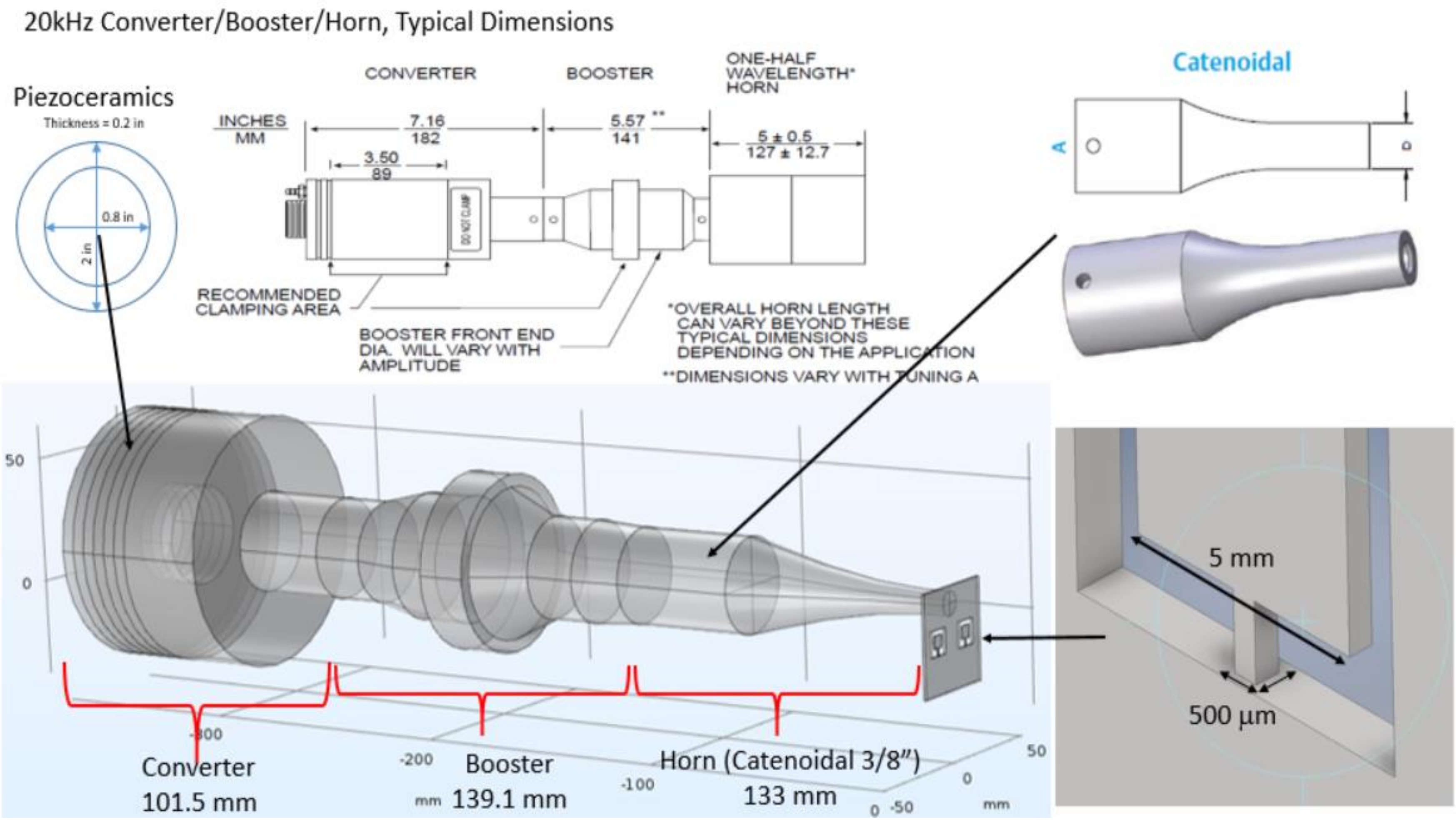
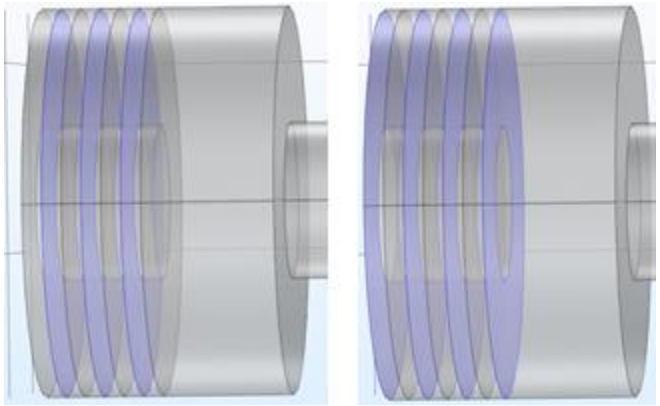


Branson Ultrasonics Corporation.

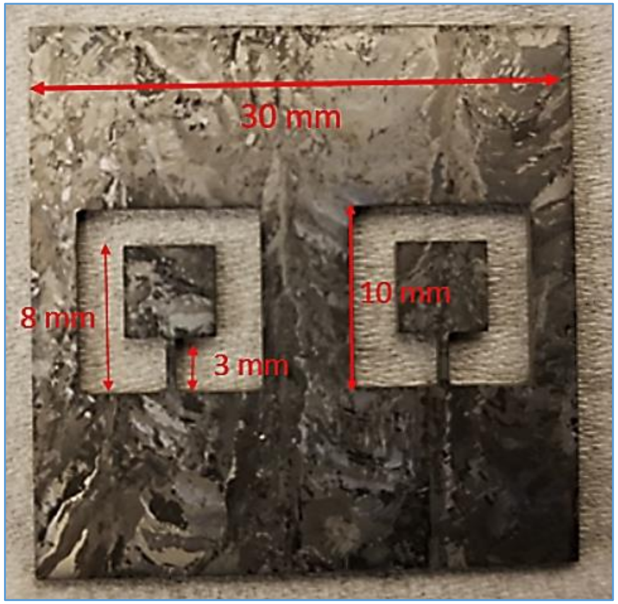
Resonance system



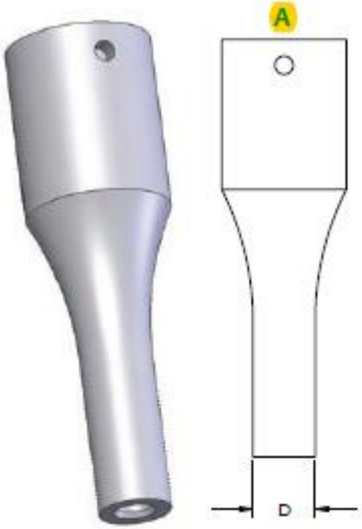
Electric potential (V)   Ground

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

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



Catenoidal Horn



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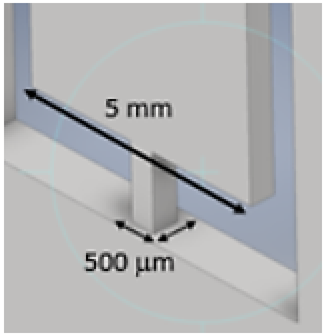
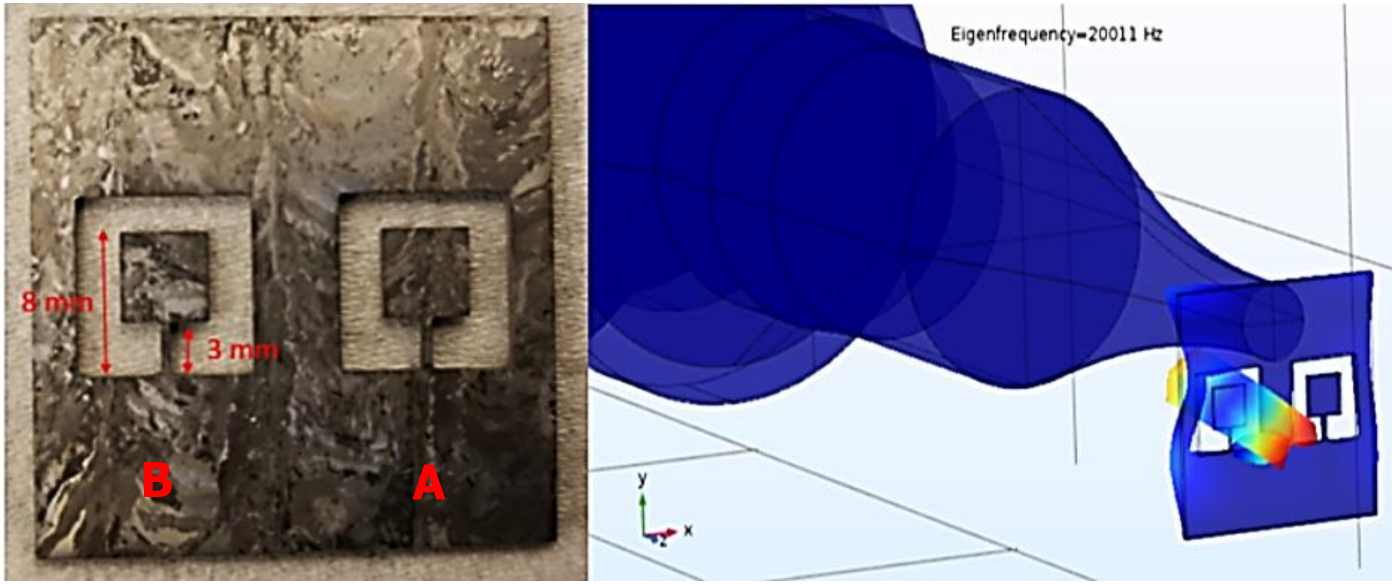


Sample dimensions

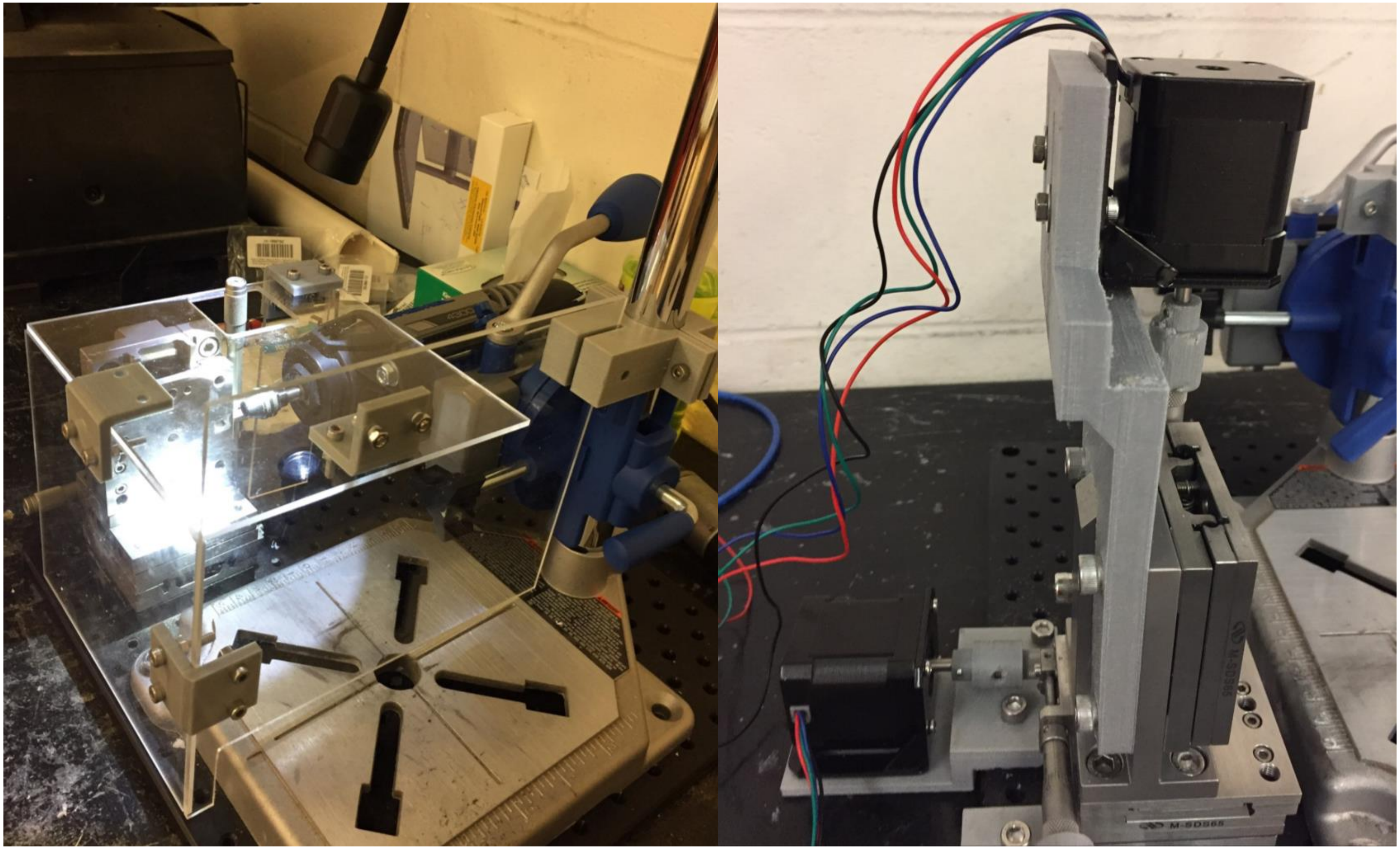
Ultrasonic Fatigue Test Expectation on EBAM-Ti-6Al-4V



The expectation respect to the *S-N* curves and fracture analysis are that crack propagation in zone B would be lower than in zone A. This is under the argument that in very fine lamellar microstructures with individual α' laths more randomly oriented in zone B than A, a crack would have more deviated slip systems (stronger obstacles) on those adjacent α' laths to overcome.

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

Ultrasonic Fatigue Samples Preparation

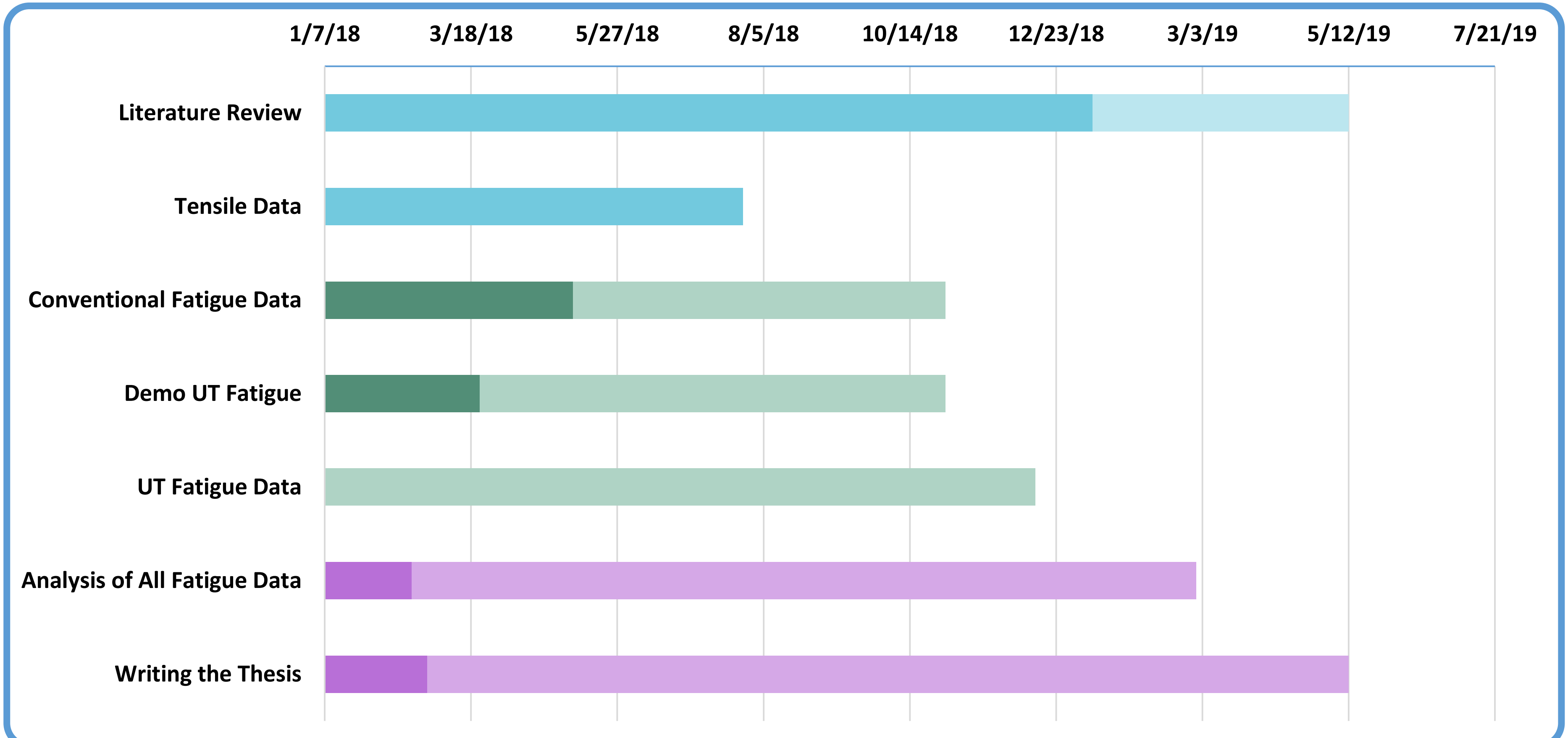


Somashekara Makireddypalli-Adinarayan / Michael Mendoza

Summary of Pending Work

- Larger EBSD maps to improve statistics on texture
- TEM-PED for dislocation density measurements and α' confirmation
- S-N curve construction and analysis from conventional fatigue test
- Final sample preparation for ultrasonic fatigue test
- Testing the resonance system at Branson Ultrasonic Corporation
- S-N curve construction and analysis from ultrasonic fatigue test
- Analysis and comparison of the fatigue tests

Progress Gantt Chart



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Thank you very much!

Michael Mendoza

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Student: *Michael Mendoza*

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Industrial Partners: *Honeywell*

Project Duration: *January. 2017 – May 2019*

Achievement

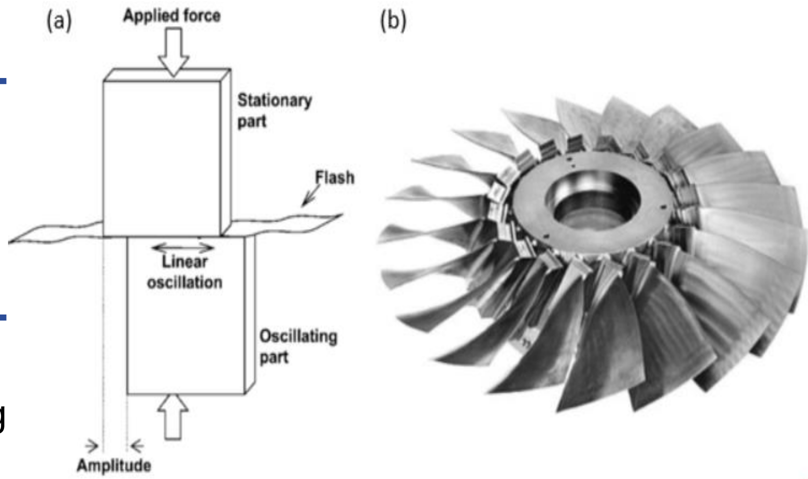
- Characterize local microstructures of Linear Friction Welding (LFW) and their relationship with mechanical properties.

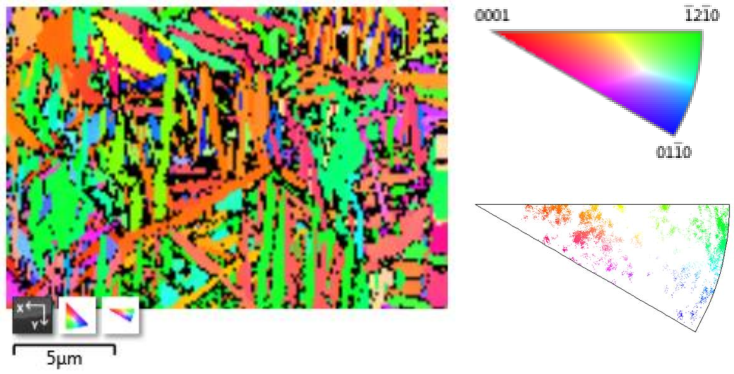
Significance and Impact

- 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.





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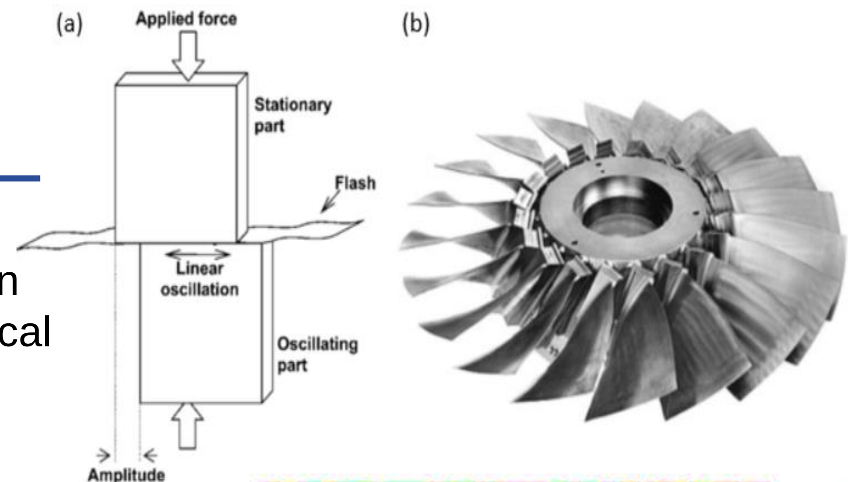

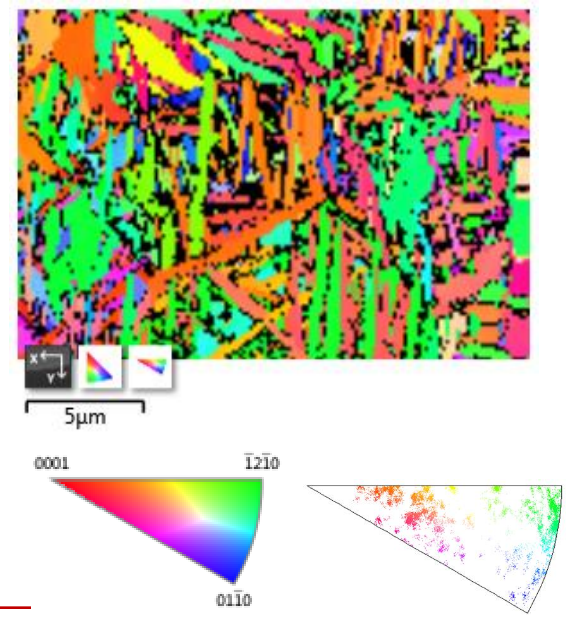

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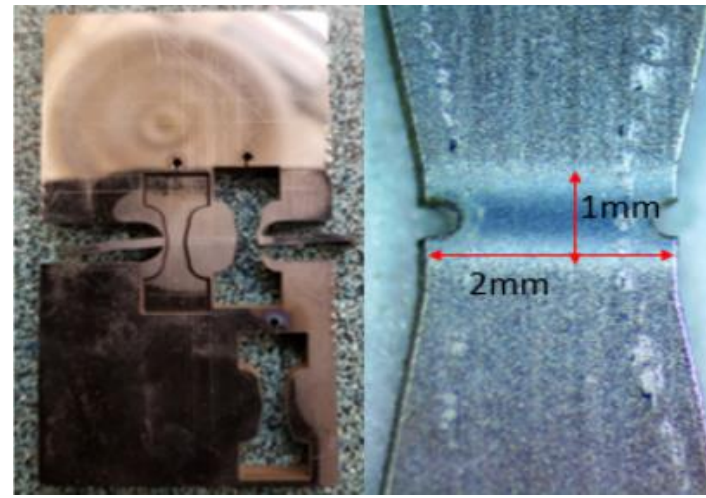

Program Goal

- 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.