ON THE INFLUENCE OF MICROSTRUCTURAL FEATURES OF LINEAR FRICTION WELDING AND ELECTRON BEAM ADDITIVE MANUFACTURING TI-6AL-4V ON TENSILE AND FATIGUE MECHANICAL PROPERTIES

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35.1 Project Overview and Industrial Relevance

This research provides a study of Linear Friction Welding (LFW) and Electron Beam Additive Manufacturing (EBAM) of the alloy Ti-6Al-4V. Currently these technologies are suitable for many aerospace applications and, in particular for integrated blisks (i.e. aeroengine compressor discs with blades). However, more studies to understand the individual microstructure influence on mechanical properties are required. In this work, dogbone shape specimens were extracted from LFW-Ti-6AL-4V to individually assess the tensile mechanical properties of the Welded Zone (WZ), Thermo-mechanically affected Zone (TMAZ) and the Parent material zone (PM) across the weld line. Beam shape specimens were also extracted from EBAM-Ti-6Al-4V to evaluate the individual microstructure influence on fatigue mechanical properties by a four-point bending test. Finally, COMSOL Multiphysics software was used to predict shape and dimensions of cantilever specimens from EBAM-Ti-6Al-4V to again assess the individual microstructure influence on fatigue mechanical properties, but to a very high cycle's regime (10^9 Cycles). For this last section, a commercial ultrasonic welding machine will be adapted to perform the fatigue tests.

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.

35.2 Previous Work – Literature Review

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. Each manufacturing process (e.g. LFW, EBAM, LENS, Casting, etc.) has its own particularities in terms of thermal or thermomechanical histories that affect local microstructures. However, we will focus on LFW that offers unique thermomechanical conditions and EBAM that provides bigger microstructural features than other AM processes which makes the analysis easier. Linear Friction Welding LFW is a solid-state joining process of two workpieces under compressive forces [35.1] (Fig. 1a). During the process, one workpiece is stationary while the other one is in motion, this friction generates heat that plasticize the contact zone and a final forging pressure is applied to consolidate the joint [35.2]. The current and major use of LFW is for joining of aeroengine compressor discs with blades to form blisks [35.3-6] (Fig. 1b). However, there is more recent interest for aircraft structural components made of Ti-6Al-4V [35.6]. 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. Smaller workpieces can be joined with LFW to produce a component, so less material is required as an initial step [35.6]. Vairis and Frost [35.7, 8] describe the process into four distinct phases. At phase I, the two workpieces are placed into contact under certain pressure. The contact area is augmented with reduction of asperities and heat generation due to solid friction. In phase II, the heat generation is enough to increase the area of contact to a 100% and expulsion of viscous material from the interface (i.e. initial flash formation). In the specific case of Ti-6Al-4V, it is when the interface reaches the β-transus temperature [35.9]. Phase III is the equilibrium phase, here the flash formation is more visible and the axial shortening is present at a constant rate [35.6]. Phase IV is known as deceleration and forging phase where in less than 0.1 s the two workpieces are brought to rest and a final forging pressure is applied to finish the joint. LFW-Ti-6Al-4V can produces three different zones, parent or base material (PM) with a bi-modal microstructure (i.e. primary α_p grains surrounded by a lamellar microstructure of α laths

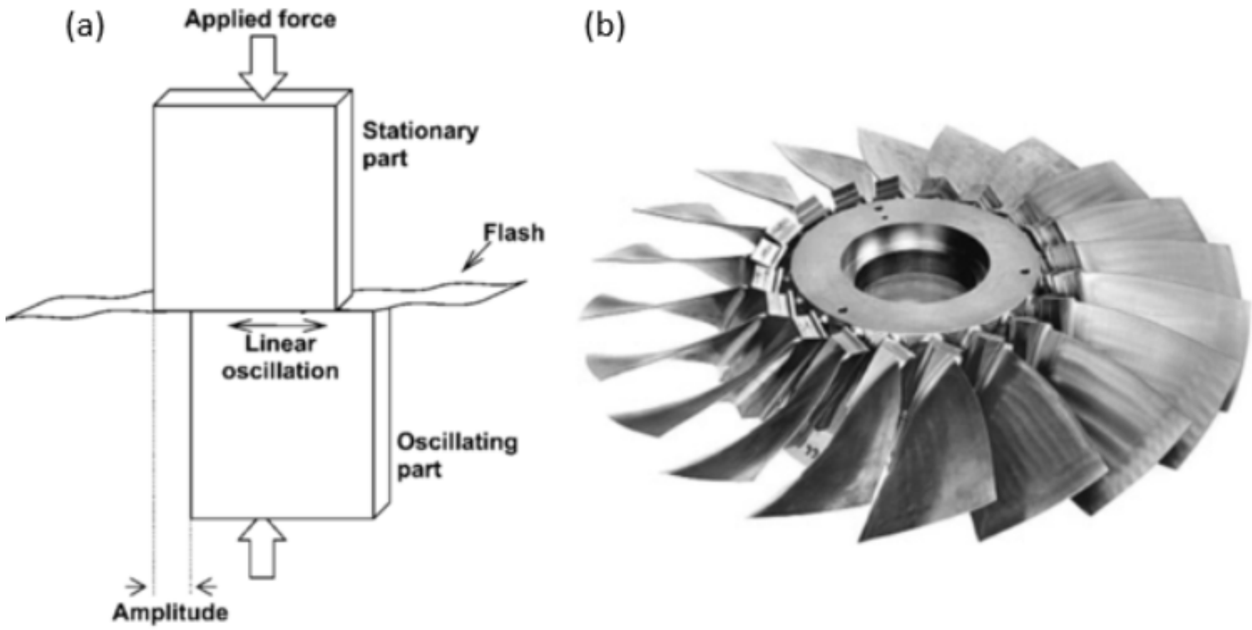

Figure 1.(a) Diagram of Linear Friction Welding process, (b) Integrated blisk (disc and blades) [35.3].

in a β matrix), thermo-mechanically affected zone (TMAZ) with a distorted bi-modal microstructure and a weld zone (WZ) with a refined martensitic α' (needle-like) or a widmanstatten microstructure depending on the cooling rate (Fig. 2).

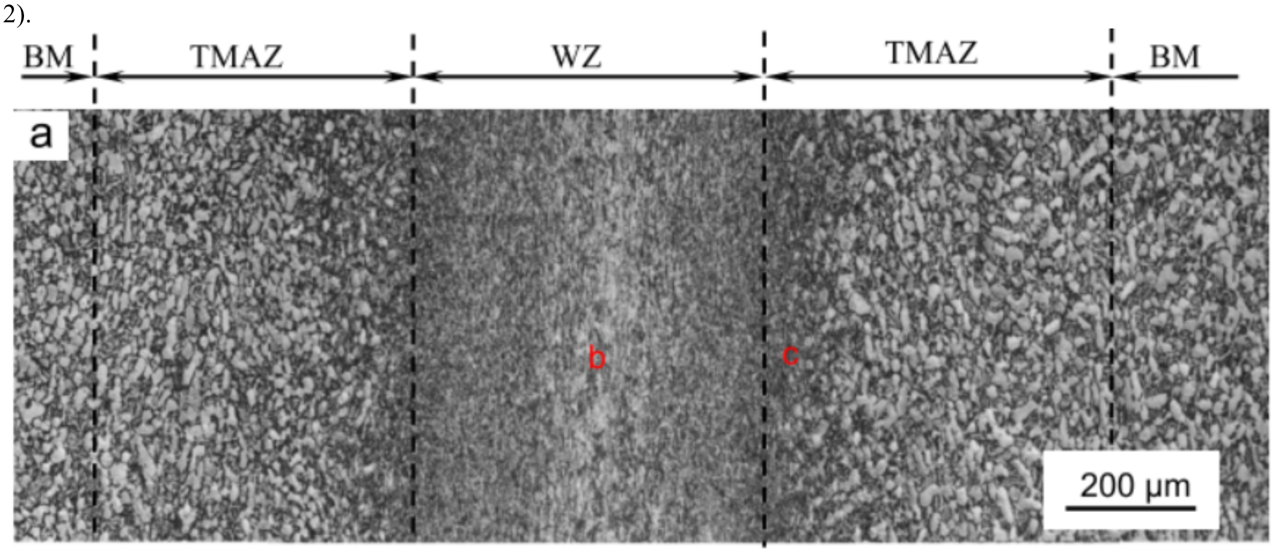

Fig. 2 Microstructure change across a LFW joint [35.10].

As mentioned, this research focus into the Ti-6Al-4V alloy and some mechanical properties according to the microstructure as a consequence of the manufacturing process. The conventional approach to evaluate tensile mechanical properties for LFW of Ti-6Al-4V is by consideration of processing parameters as the frequency of oscillation, amplitude, frictional pressure and axial shortening [35.1, 6, 11-13]. However, our approach will be just to evaluate specific tensile properties of given LFW-Ti-6Al-4V microstructures at certain constant processing parameters. To date most of the results for tensile test show failure at the parent material zone (PM) if not interface contaminants are present [35.1, 6, 11-13]. However, Wanjara and Jahazi [35.1] also showed that failure can also occur on the TMAZ due to a low power input that reduce the cooling rate after oscillatory motion, making the alpha laths bigger which in turn makes the TMAZ weaker than PM [35.6]. Our approach is to evaluate the specific tensile properties of the three zones of LFW-Ti-6Al-4V by forcing the tensile samples to fail at the respective zone. Characterization techniques as SEM, EBSD, TEM and PED will help us to determine the reasons of those differences in tensile properties.

Additive manufacturing process (AM), also known as 3D printing is a rapid solidification process that involves several factors affecting the final microstructure. By definition AM is a process where a local heat source (e.g. laser, electron beam, plasma) melts a source of material (e.g. incoming powder flow, wire, powder bed) on a substrate of similar characteristics of the material [35.14]. The relative motion between the heat source and the substrate allows the melted material deposition to occur layer by layer, always under a computer aid control from a CAD file [35.14] (Fig. 3). This particular way to produce parts offers several advantages as near net-shape components with very low final machining required, complex parts are easy to make with the right CAD file, less waste of material as compared with subtractive manufacturing technologies and new possibilities in terms of microstructure control.

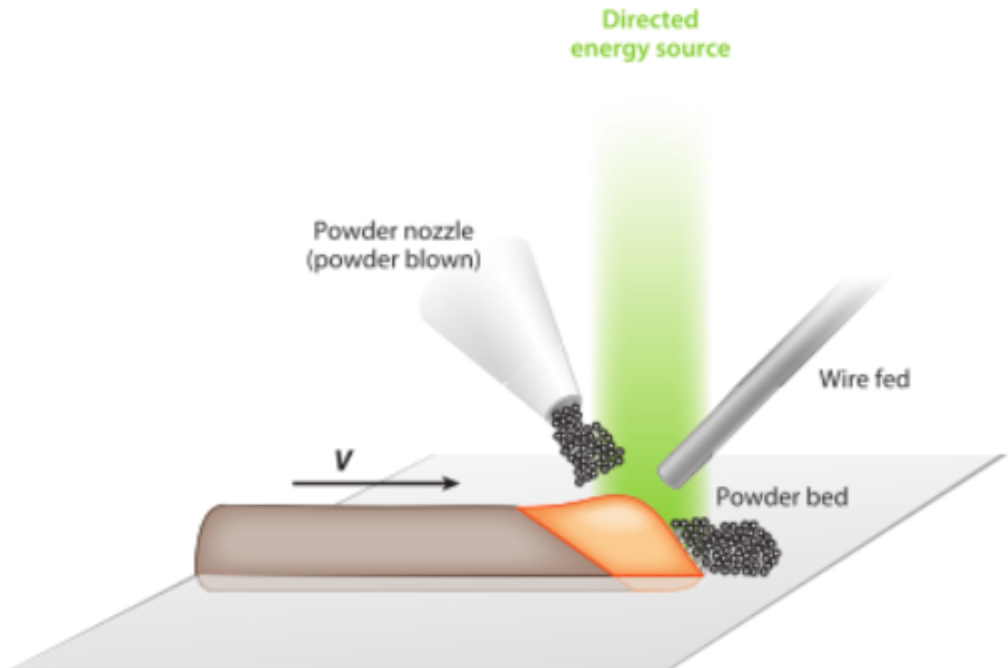

Fig. 3 Schematic AM process showing a single pass [35.14].

In this study, we will focus into the Electron Beam Additive manufacturing technique EBAM that uses an electron beam as heat source, Ti-6Al-4V wire as feedstock and a vacuum chamber to protect the alloy to react with oxygen. In Fig. 4 characteristic features of EBAM-Ti-6Al-4V are observed in the *z-y* cross-section being *x* the direction of deposition (out of paper). Two distinct zones can be recognize on this picture, zone A comprises vertically elongated prior β grains with very little variation in α lath thickness due to the uniform and strong epitaxial growth from bottom to top [35.15]. On the other hand, Zone B has a pronounced variation in α lath thickness and a more scattered orientation due to the competing growth from the side wall of the molten pool [35.15]. Several tensile tests were already reported on those microstructures to assess their influence on tensile mechanical properties [35.15]. Therefore, the interest of this research is in mechanical properties from a fatigue test on those two type of microstructures. Four-point bending test is selected as a convenient method for fatigue studies due to several reasons (Fig. 5). It typically works with rectangular beams that produce a uniform maximum stress on the surface, depending of the distance between inner rollers [35.16]. Easy sample mounting and dismounting as no special gripping is required. It is also suitable to evaluate specific microstructures from small samples, T. Zhai et al. [35.16] reported specific sample and device dimensions to perform the four-point bending test. The optimum testing geometry to achieve a uniform stress distribution consistent with the calculated value of beam theory, requires a load span/specimen thickness ratio (*t/h*) between 1.2 and 1.5. It also requires a support span/load span ratio (*L/t*) between 4 and 5 [35.16].

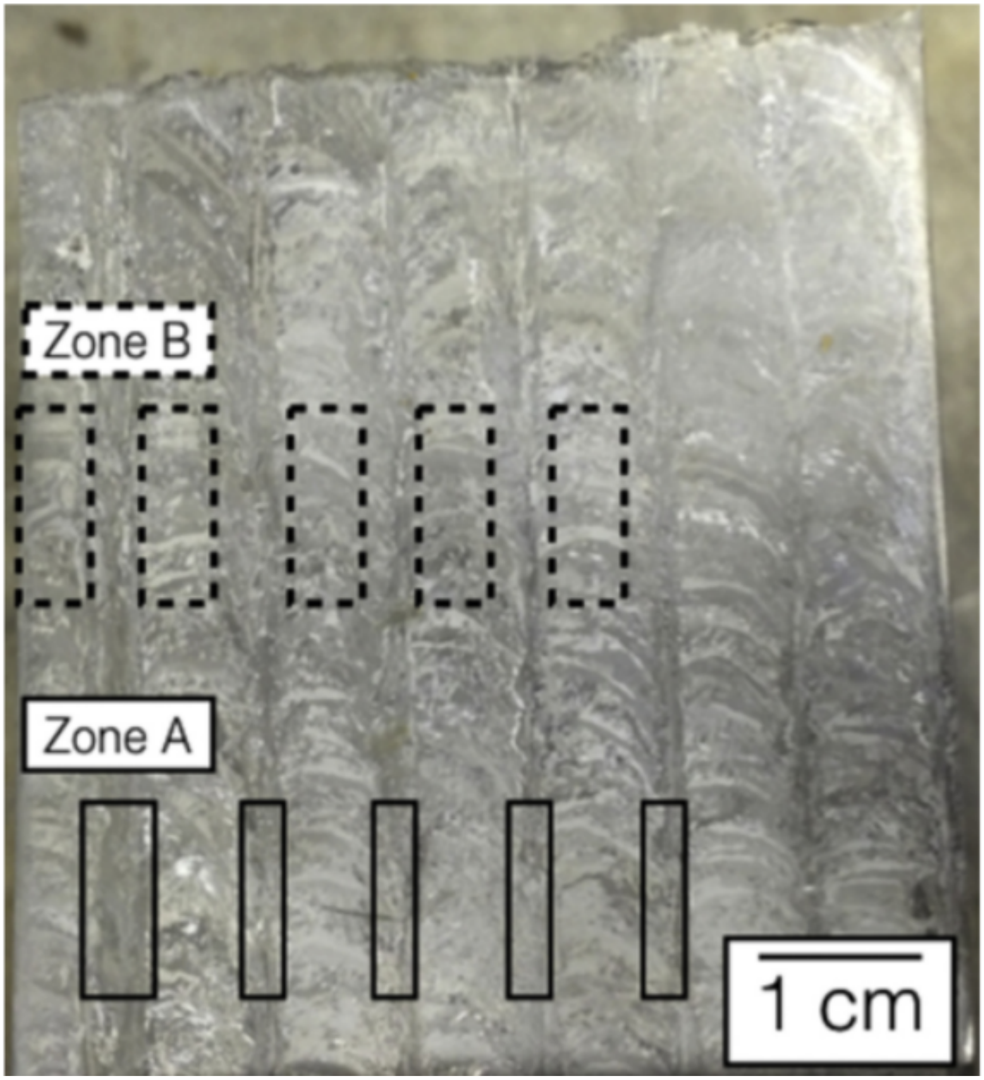

Fig. 4 Z-Y Cross-section of an ELI Ti-6Al-4V build [35.15].

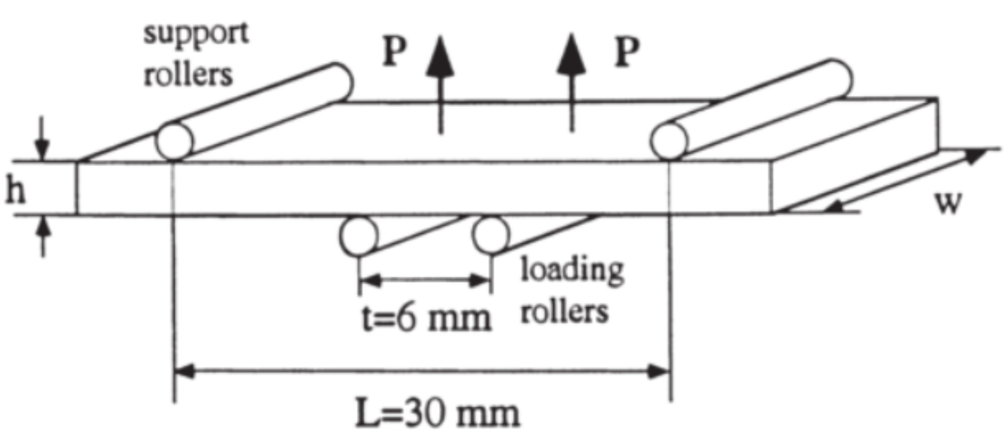

Fig. 5 Four-point bend specimen geometry and the loading states [35.16]

Conventional fatigue approach provides useful information of mechanical properties. However, several applications of Ti-alloys (e.g. Ti-6Al-4V) are required to safe operation over long periods of time, extending 10^9 cycles [35.17]. Conventional fatigue tests as electromagnetic shakers or servo-hydraulic systems can achieve 10^9 cycles in weeks, so a single S-N curve would last months [35.18]. This approach is impractical to understand the material behavior in this regime. Therefore, ultrasonic fatigue testing offers an alternative where 10^9 cycles can be reached in less than a day. An ultrasonic fatigue system contains a generator, transducers (piezoelectric elements that generate the mechanical movement), booster, acoustic horn (typically acting as amplifier) and specimen (Fig. 6). Each part of the system has to satisfy the resonance condition [35.19]. This design is made in a way where the specimen has specific dimensions to offer a mode shape with maximum amplitude deformation on the specimen and not on any other part of the system [35.19-21]. Usually 20 KHz ± 500 Hz is the Eigenfrequency used to perform fatigue tests, a more detailed ultrasonic fatigue testing description can be found in [35.18-20, 22, 23]. Our approach here is again to evaluate a selective microstructure of an EBAM-Ti-6Al-4V process as for the conventional fatigue case (10^7 cycles), but in the regime of very high cycles (10^9). For this purpose, we will use an ultrasonic welding machine manufactured by Branson Ultrasonics with certain modifications to perform the fatigue test. The pre-selection of booster, horn, specimen shape and dimensions will be based on simulations of the process by COMSOL Multiphysics. A more detailed description of the general steps for the simulation can be found in [35.24].

In this study, we have three general objectives. First, we will assess tensile mechanical properties of the individual LFW zones as WZ, TMAZ and PM. Second, we will evaluate conventional fatigue mechanical properties of two zones (microstructures) of an EBAM-Ti-6Al-4V process. Finally, we will extend the analysis of the fatigue mechanical properties of the EBAM-Ti-6Al-4V process under the very high cycle regime. Additionally, we will adapt an ultrasonic welding machine into an ultrasonic fatigue machine.

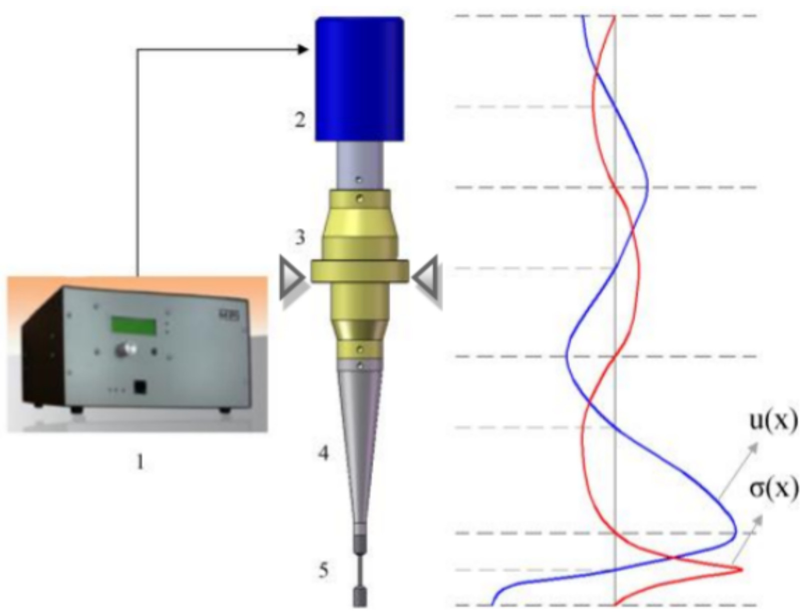

Fig. 6 Ultrasonic fatigue testing machine. 1-generator, 2- transducer, 3-booster, 4-horn, 5-specimen. u(x) displacement, ?(x) stress [35.24]

35.3 Technical Plan and Recent Progress

Dogbone shape samples were extracted via EDM (Electron Discharge Machining) according to the availability of LFW-Ti-6AL-4V material to capture the three zones of the process (Fig. 7). Measurements of microhardness on each zone help us to determine the appropriate cross-section area to guide the tensile test on each specific zone (i.e. WZ, TMAZ and PM). A ZwickLine Z2.5TN with screw grips type 8253 was used for the tensile test of the three LFW zones and the TestXpert II software registered the respective Stress/Strain data and curves (Fig. 8).

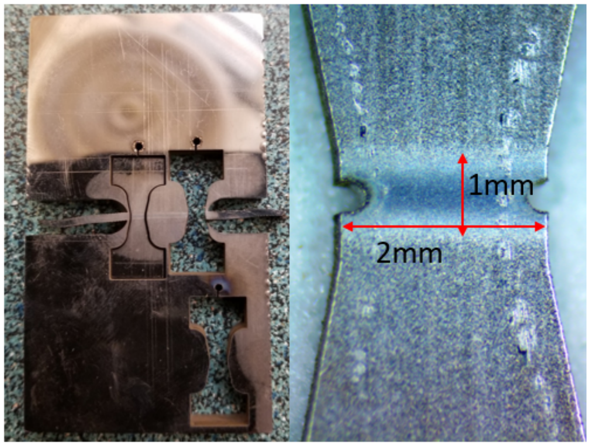

Fig. 7 Tensile test specimens extracted from the LFW-Ti-6Al-4V.

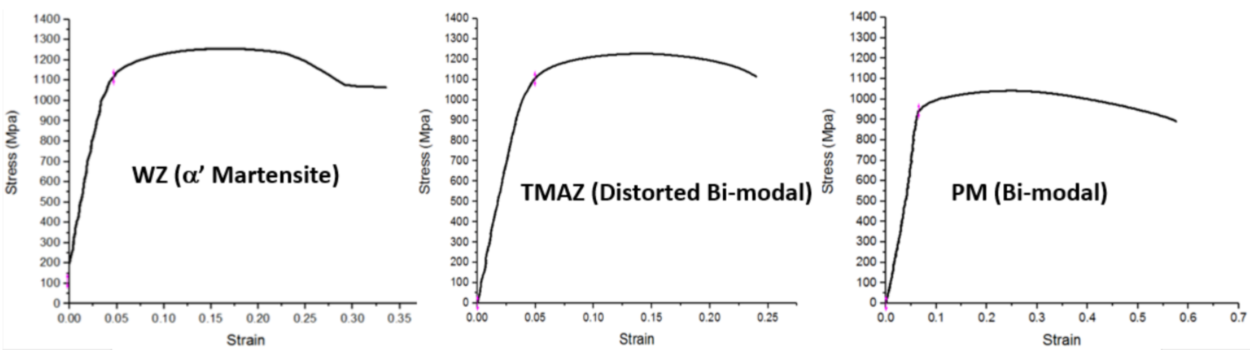

Fig. 8 Stress/ Strain curves for the three LFW-Ti-6Al-4V zones.

From this data, we can see preliminarily that the yield strength is ~14% for the TMAZ and ~21% for the WZ greater than the PM zone. We know from similar tensile tests on LENS-Ti-6Al-4V that the yield stress is between 1 and 10% greater than the PM zone due to the martensitic microstructure. This difference suggests that another hardening mechanism is taking place.

Table. 1 Tensile properties of LFW-Ti-6AL-4V zones.

	$Y_{0.2\% (Mpa)}$	$U_{TS (Mpa)}$	$R_{S (Mpa)}$	%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

In order to understand what mechanism is involved, TEM and PED analysis should be performed on the WZ to confirm the presence of the α’ martensitic microstructure similar to the one observed on common LENS-Ti-6Al-4V specimens. Knowing from literature that the modulus of elasticity E of α titanium single crystal is inversely proportional of angle γ between the c-axis of the unit cell and the stress axis, polycrystalline α titanium with texture has to be considered. For this purpose, EBSD maps of all three zones will be useful to evaluate the influence of texture on the tensile mechanical properties.

To assess the conventional fatigue mechanical properties of zones A and B (i.e. microstructures of EBAM-Ti-6Al-4V) a four-point bending test will be performed. 20 specimens total, 10 for zone A and 10 for zone B were sectioned via EDM with the suitable dimensions for capturing the interested microstructure (Fig. 9). The specimens were chamfered on sharp edges and polished on surfaces to be tested at Westmoreland Mechanical Testing and Research, Inc. The S-N curve and fracture mechanics will be evaluated on those two microstructures.

Fig. 9 Conventional fatigue beams sectioned via EDM, chamfered, polished and etched.

Ultrasonic fatigue test demands an extra effort on this study. First, the ultrasonic system is modeled with COMSOL Multiphysics to see its response by trial and error changing the acoustic horn, shape and dimensions of the test specimen. All the information of the ultrasonic system is provided by Branson Ultrasonics (Fig. 10). The response should match with an estimated lower stress on specimen of 460 Mpa and a higher stress of 980 Mpa (common limit values for a regular S-N curve of Ti-6Al-4V). The sequence of this modeling is first to determine the Eigenfrequency around 20 kHz with the desired mode shape on cantilevers. Once the eigenfrequency is determined a frequency domain study is done to determine the input power values for the system to show the stress levels required to match. The cantilever specimens with the calculated dimensions were sectioned via EDM, polished and etched. The Zones A and B of the EBAM-Ti-6Al-4V material are clearly visible on the etched specimen in Fig. 11. However the thickness reduction required by the model on the cantilevers can not be performed by EDM, then a special mini Grinder/polisher similar to a GATAN Dimpler was designed and built for this purpose. The predicted eigenfrequency and the correlation of the stress levels with the amplitude displacements from COMSOL Multiphysics will be corroborated with the experimental data from the Branson ultrasonic equipment. We assume a successful prediction and a close performance of the test to construct the S-N curve in the regime of 10^9 cycles to assess the fracture mechanics.

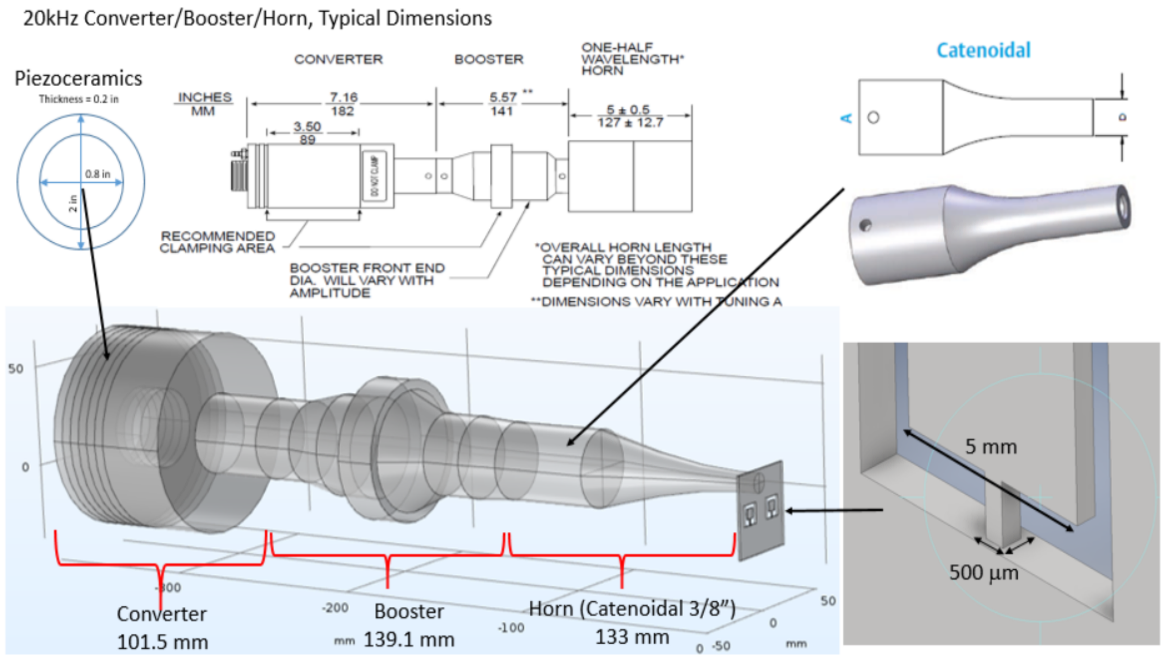

Fig. 10 Comsol model of the ultrasonic fatigue system according to Branson Ultrasonic equipment.

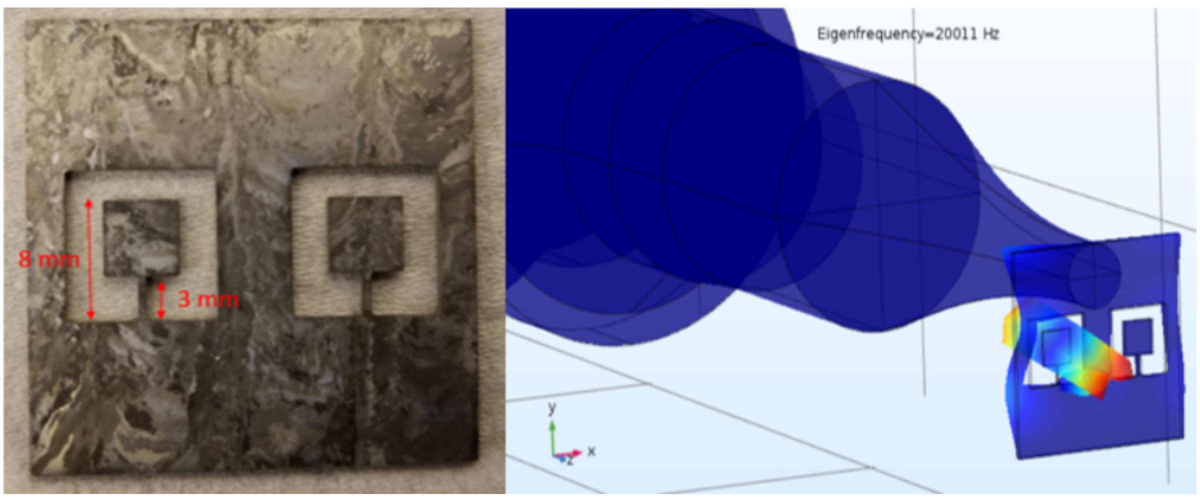

Fig. 11 Cantilever sectioned via EDM with the calculated dimension, and the mode shape of cantilever vibration.

35.4 Expected Results

For the LFW-Ti-6Al-4V section, 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. We believe that the mechanism that is acting is strain hardening, from this perspective dislocation density measurements are necessary to differentiate the WZ and the LENS-Ti-6Al-4V microstructures. Additionally, we expect to see a strong transverse texture. In other words, the c-axis of the α' hexagonal crystallites are predominantly parallel to the transverse direction or perpendicular to the reciprocating motion and axial direction. This expected texture has a negative influence on the yield strength on the WZ, then it makes the argument of strain hardening even stronger.

On the four-point bending fatigue experiment, we know that the zone B has a bigger variation in α' lath thickness and orientation. We expect 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. Therefore, if there is a difference in the S-N curves for those microstructures would be in that direction.

The ultrasonic fatigue test offers even more challenges. First, we expect the prediction of COMSOL Multiphysics model to be close to the experimental determination of the eigenfrequency and second that the correlation of oscillation amplitude with stress can be also verified with the experimental test in Branson Ultrasonics. The expectation respect to the S-N curves and fracture analysis are about the same as for the conventional fatigue analysis (four-point bend test), but with the uncertainty of the different strain rate and very high frequency influence on the test.

Our objectives in terms of publications are at least two. First, tensile properties on individual LFW zones have not been studied in detail to date. Second, EBAM-Ti-6AL-4V process has been studied before and tensile properties have been reported in the past, but fatigue analysis have not been performed on those individual microstructures to date. Additionally, even when ultrasonic fatigue test is not new, there is just a few studies on it and no one specifically on EBAM-Ti-6Al-4V.

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