Mechanical property evaluation of Ti-6Al-4V parts made using Electron Beam Melting

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Abstract

Cylindrical Ti-6Al-4V parts were built in vertical and horizontal orientations using electron beam melting. Tensile tests and fatigue tests were carried out. The specimens were tested in as-built and machined conditions to understand the effect of surface finish on mechanical properties. The fracture surfaces were analyzed using scanning electron microscopy and the fractography results were correlated with the mechanical properties. Based on the results the effects of part orientation and surface finish on mechanical properties are discussed.

Introduction

Electron beam melting (EBM) is a relatively new addition to metal additive manufacturing technology. The process was commercialized by Arcam AB (Sweden) in 2002. EBM machines built by Arcam are being used for both commercial and research purposes. Promising areas for practical application of this technology are in the biomedical [1,2] and aerospace [3] industries. The EBM technology has the ability to fabricate three dimensional dense mechanical parts with properties comparable to wrought titanium and better than cast titanium [4]The EBM system consists of an electron beam generating system (an electron gun), a vacuum build chamber, a powder feed system and a computer to control the whole process. The vacuum build chamber minimizes the problems of atmospheric contamination and porosity to a large extent. The working principles of an EBM machine are well documented in the literature [5]. Research has been underway to gain better insights on different aspects of the parts fabricated by the EBM process. Ti-6Al-4V processed by EBM results in fine Widmanstatten α laths due to the phase transformation from columnar prior β grains. This phase transformation is extremely beneficial as there is no preferred texture due to the absence of columnar grains [6].

One of the main advantages of additive manufacture (AM) is the geometric freedom involved in fabricating components. However, there can be a difference in part properties with respect to the orientation at which the part has been built. One common way to use EBM is to produce near-net shaped structures which are finished machined to tight tolerances for demanding applications. Although this machining can achieve the required dimensional accuracy, the differing surface conditions between machined and unmachined regions of a part may impair the mechanical behavior. Therefore, this study investigates the mechanical behavior of EBM built parts with respect to the build orientation and surface condition.

Experimental methods

The material used for this study was Ti64 ELI powder (approximate chemical composition (wt%) : 6 Al, 4 V, 0. 03 C, 0.01 N, 0.1 O, 0.1 Fe and balance Ti) supplied by Arcam. Ti64 is the workhorse material for biomedical implants and aerospace components due to its high specific strength, bio-compatibility, stiffness and good corrosion resistance. The average particle size was measured using a Microtrac S3000 particle size analyzer. The average particle size was found to be 60.8 μm and the powders exhibited spherical morphology.

An Arcam EBM S400 and the Arcam-provided standard process parameter theme for Ti64 were used to build the parts. The build chamber was maintained at a constant temperature of 650 ^{o}C and a vacuum pressure of 7 x 10^{-4} Torr.

Test specimens were fabricated for tensile and fatigue tests in both vertical and horizontal orientations conforming to ASTM standards (ASTM E8M for tensile and ASTM E 466 for fatigue). Another batch of samples was fabricated with 1 mm machining tolerance and then CNC machined to the ASTM standard dimensions. No Post-heat treatment or HIPing was carried out for the specimens.Tensile testing was carried out in an Instron 50 kN test machine (Model: 5569A) and fatigue testing was carried out within the high cycle fatigue range using an Instron 10 kN fatigue machine (Model: Electropulse E10000). The fatigue test was performed at R=0.1 using a 50 Hz sinusoidal wave form under load control to a maximum of 10^7 cycles. R=0.1 corresponds to a tension-tension cycle in which the minimum stress is equal to 0.1 times the maximum stress. By keeping the stress ratio R to a lower value, the mean stress remains low and therefore high stress amplitudes can be sustained for the material without fracture. The fatigue test was conducted at an ambient temperature of 22 ^{o}C and a relative humidity of 45 %.

The tensile and fatigue fracture surfaces were examined using a FEI Nova Nano scanning electron microscope (SEM). Metallographic samples were prepared from the specimens for optical micrography (OM) and SEM using standard metallographic sample preparation methods. Ti64 samples were etched with Kroll's reagent.

Results and Discussions

Tensile Characteristics

Tensile tests were carried out for specimens fabricated in horizontal and vertical orientations with as-built near-net tensile samples and machined tensile samples. The tensile test results are shown in Table 1 and the corresponding stress-strain curves are shown in Fig.1. Five tests were carried out in each case and the mean value is reported. The yield strength, ultimate tensile strength, elastic modulus, and percentage strain were obtained as direct output from the tensile testing machine. The percentage strain-to-failure was measured using a clip-on extensometer that was attached to the gage section of the test specimen.

Table 1: Tensile test results for EBM Ti64 samples built in horizontal and vertical orientation

<table>
<tr><th colspan="2"></th><th>Stress at Yield [Offset 0.2 %] (MPa)</th><th>Ultimate tensile stress (MPa)</th><th>Strain at break (%)</th><th>E-Modulus (GPa)</th></tr>
<tr><td colspan="2">As-built vertical</td><td>782 (SD:5.1)</td><td>842 (SD: 13.84)</td><td>9.9 (SD: 1.02)</td><td>101 (SD:2.5)</td></tr>
<tr><td colspan="2">As-built horizontal</td><td>844 (SD:21.6)</td><td>917 (SD:30.53)</td><td>8.8 (SD:1.42)</td><td>104 (SD: 2.3)</td></tr>
<tr><td colspan="2">% increase</td><td>8</td><td>9</td><td></td><td></td></tr>
<tr><td colspan="2">Machined vertical</td><td>869 (SD:7.2)</td><td>928 (SD:9.8)</td><td>9.9 (SD:1.7)</td><td>115 (SD:0.7)</td></tr>
<tr><td colspan="2">Machined horizontal</td><td>899 (SD: 4.7)</td><td>978 (SD: 3.2)</td><td>9.5 (SD:1.2)</td><td>113.5 (SD: 2.5)</td></tr>
<tr><td colspan="2">% increase</td><td>4</td><td>5</td><td></td><td></td></tr>
<tr><td colspan="2">ASM Handbook(1993) (Cast and annealed)</td><td>885</td><td>930</td><td></td><td></td></tr>
<tr><td rowspan="2">% increase in machined compared to as-built</td><td>Vertical Orientation</td><td>11</td><td>10</td></tr>
<tr><td>Horizontal Orientation</td><td>6.5</td><td>6.6</td></tr>
</table>

SD: Standard Deviation

The tensile properties reveal that the specimens tested from the horizontally built samples have marginally higher strength values when compared to the specimens built in the vertical orientation. Surface conditions also showed some effect on the tensile properties. Both vertical and horizontal machined samples resulted in better tensile properties. For each orientation, the ultimate tensile strength of the specimens is only marginally higher than the yield strength indicating the work hardening rate beyond yield to be low. The tensile results for both orientations are comparable to standard Ti64 cast and annealed material [7].

The tensile strength values for vertically oriented and machined samples reported by Facchini et. al [8] are similar to the results in the current study. However the tensile strength values reported by Murr et al. are slightly higher than the values reported in this study [1]. This variation in tensile properties with respect to the build orientation can be attributed to the fabrication defects and the orientation of the defects as a function of the loading axis [9]. Defects present in the x-y plane in a vertically built sample are pulled apart as they are perpendicular to the tensile axis. In addition, microscopic discontinuity will exist at the regions were the two ends of columnar grains meet and this region also lies perpendicular to the tensile loading axis. For horizontally built samples the propensity of opening up of a defect present in the x-y plane will be low as it is aligned parallel to the tensile loading axis.

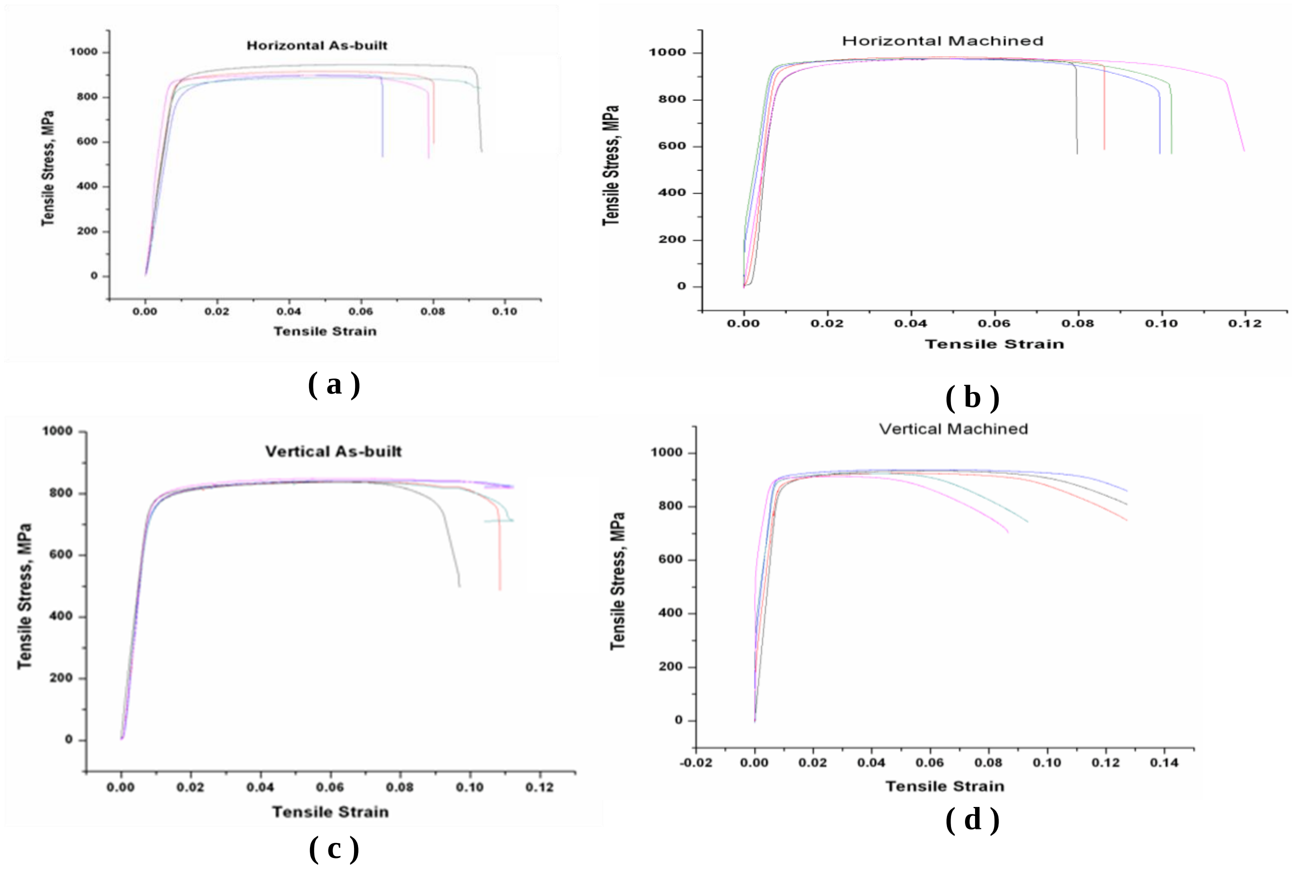
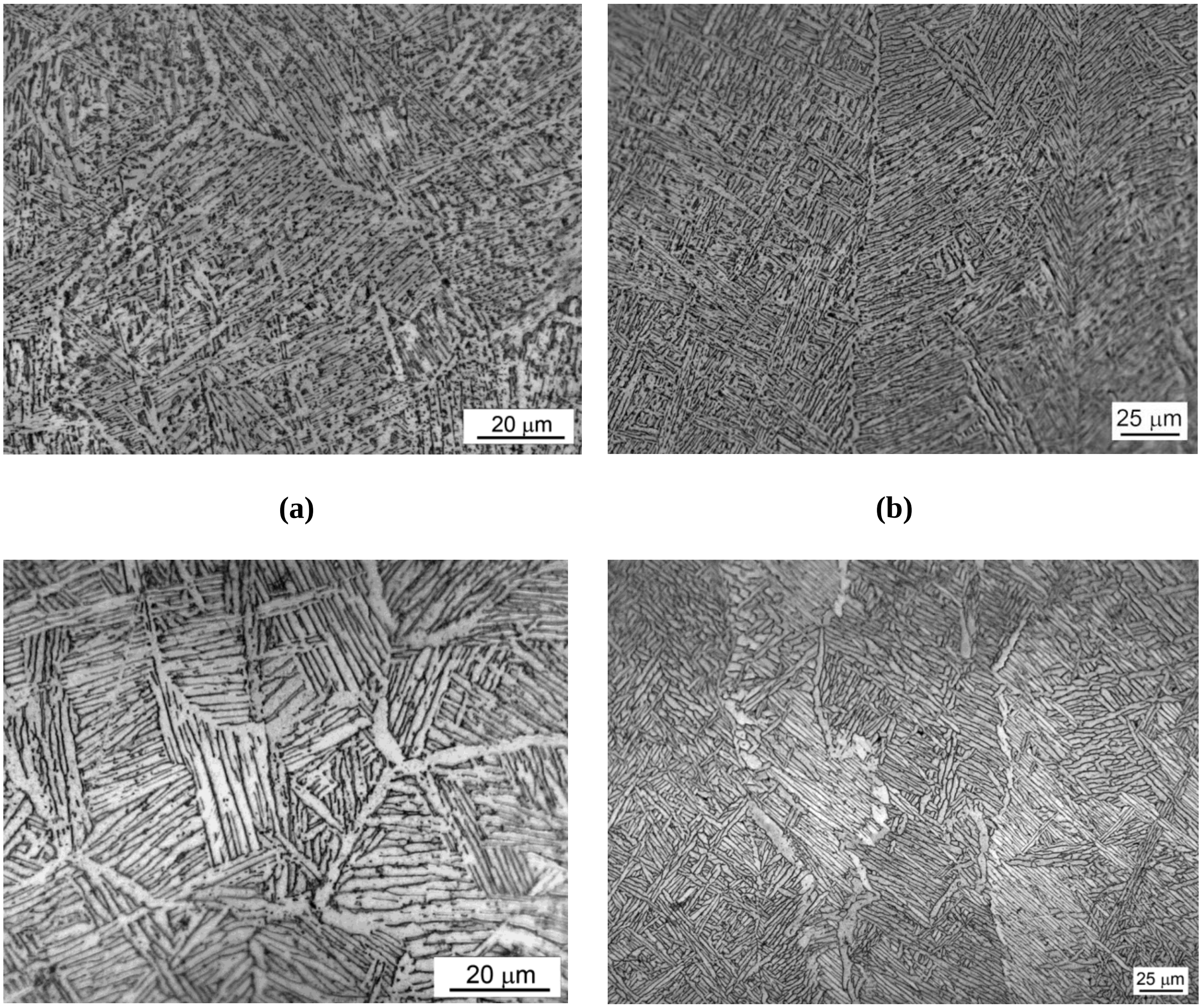


Fig.1. Stress-Strain curves for EBM built Ti64 samples. a) Horizontal as-built b) Horizontal machined c) Vertical as-built d) Vertical machined

The tensile properties can be affected by microstructural differences. Fig. 2 shows the optical micrographs of EBM fabricated Ti64 samples built in horizontal and vertical orientations. The longitudinal and transverse cross-sections of samples built in a horizontal orientation show more refined lamellar α as compared to the vertical orientation. The finer the lamellar structure, the better will be the mechanical properties. The tensile strength decreases with increase in lath width and lath colony size due to an increase in the effective slip length [6].



(a) (b)

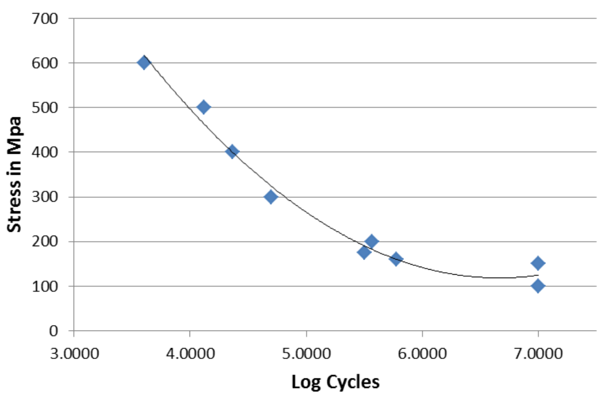
(c) (d)

Fig. 2. Optical micrographs of EBM built Ti64 samples. a) Horizontal built- longitudinal section b) Horizontal built- transverse section c) Vertical built- longitudinal section d) Vertical built- transverse section

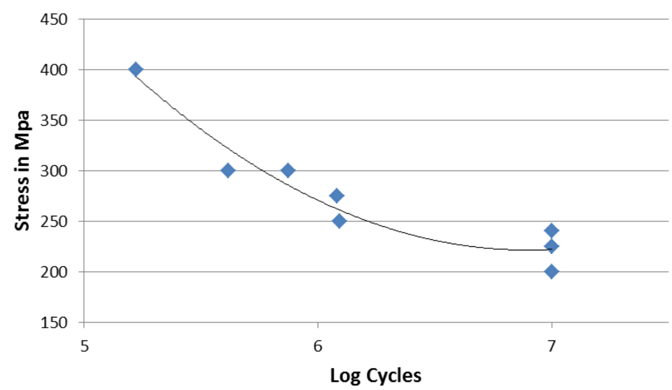
Fatigue Characteristics

The results of fatigue testing of EBM as-built and machined samples fabricated in both horizontal and vertical orientations are illustrated in Fig.3, in which the maximum stress is plotted as a function of cycles-to-failure. As expected, the fatigue limits of as-built samples are lower than the machined samples. This is because of the surface roughness in as-built samples. Between as-built vertical and horizontal samples, the horizontal samples showed better fatigue properties. This can be attributed to the layering mechanism during the fabrication of the vertical and horizontal samples.

In EBM each layer is built in two steps. First the outer boundary is melted and is processed as a "contour." The contour provides an interface between the actual build and the surrounding powder. In the second step of melting the actual part is built within the contour and is normally processed as "squares." While building a cylindrical part in the vertical orientation the contour is obtained by melting a circular path and the layer is completed by filling the circular region. When a cylindrical part is built in the horizontal orientation, the contouring is done along a rectangular path and the layer is completed by filling the rectangular region. This difference in contouring results in two different surface conditions; vertical samples resembling thin circular discs stacked one above the other and horizontal samples resembling thin rectangular sheets stacked one above the other. The stacking of layers causes the formation of stair-step ridges and/or valleys between each layer at the surface which accounts for the surface roughness. These surface features are shown in Fig.4. For a vertically built sample the valleys become perpendicular to the loading axis during fatigue testing. This results in preferential crack initiation in vertically built samples as compared to horizontal sample when tested in as-built condition. This is evident from the fatigue fracture surfaces as well (Fig.5).



(a)



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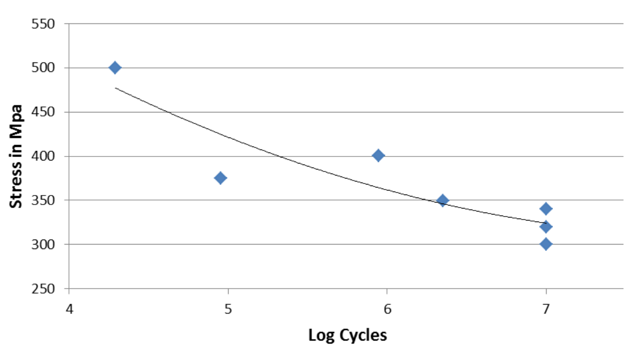

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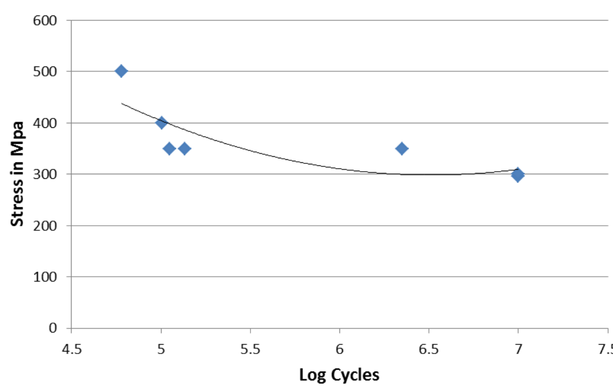


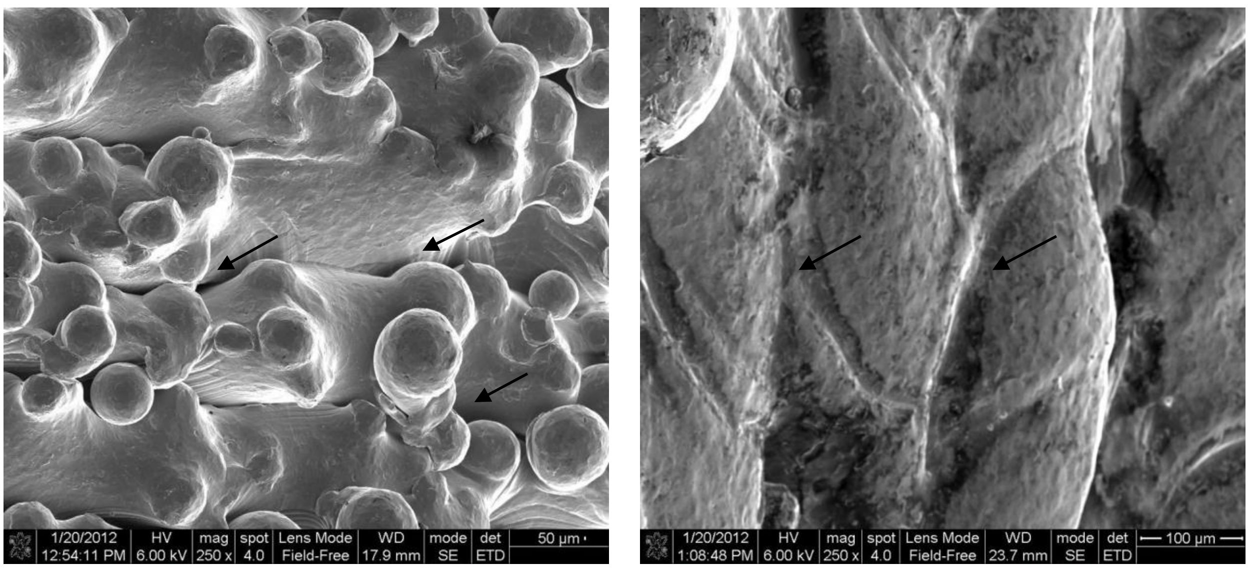
(d)

Fig.3. Stress Vs. log cycles to failure for EBM built Ti64 samples. a) Vertical as-built samples b) Horizontal as-built samples c) Vertical machined samples d) Horizontal machined samples

The fatigue fracture surfaces of vertical built samples are almost smooth, representing a faster crack initiation and propagation. The fracture surface of horizontal built sample indicates slower crack initiation and propagation with more tortuous and deflected crack propagation paths.

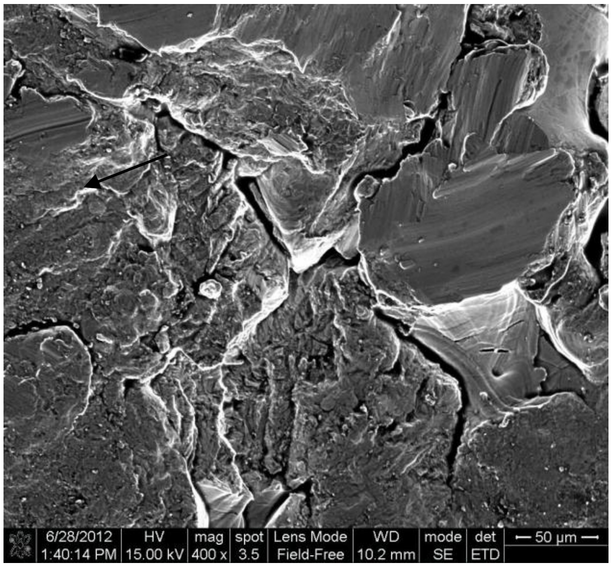
Between the machined vertical and machined horizontal built samples, the vertical built samples resulted in a fatigue limit of 340 MPa as compared to 300 MPa for horizontal built samples. Although the difference is quite marginal, the orientation of the alpha lamellae/alpha colonies with respect to the fatigue loading axis has some influence on the fatigue properties. The crack initiation in machined samples was found to be brittle in nature from the fracture surface shown in Fig.6.

Microstructure invariably affects the fatigue strength by increasing the propensity for crack nucleation and its early growth, causing premature failure of the part. In Ti64, which is an α/β titanium alloy, the cracks tend to initiate either at the surface or at the subsurface at the intersection or impingement of slip bands within the alpha lamellae of a fully lamellar microstructure.

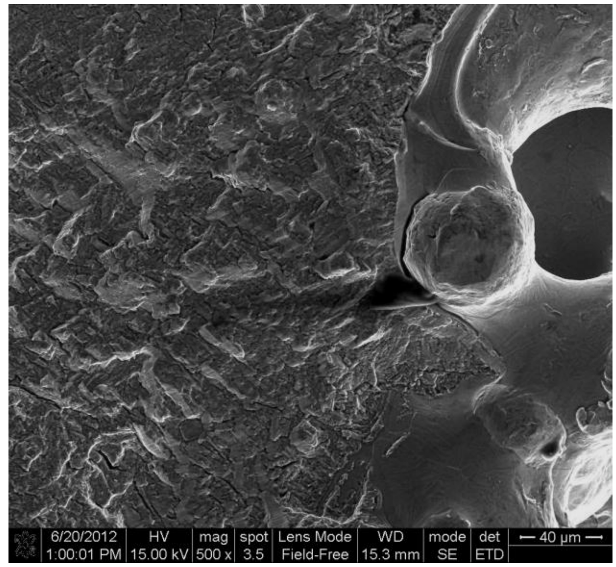


(a) **(b)**

Fig.4. SEM images of the external surfaces of EBM built samples a) Vertical built sample b) Horizontal built sample (arrow indicates ridges/valleys at the surface)



(a)



(b)

Fig.5. SEM image showing fatigue fracture surfaces (crack initiation points): a) vertical as-built b) horizontal as-built

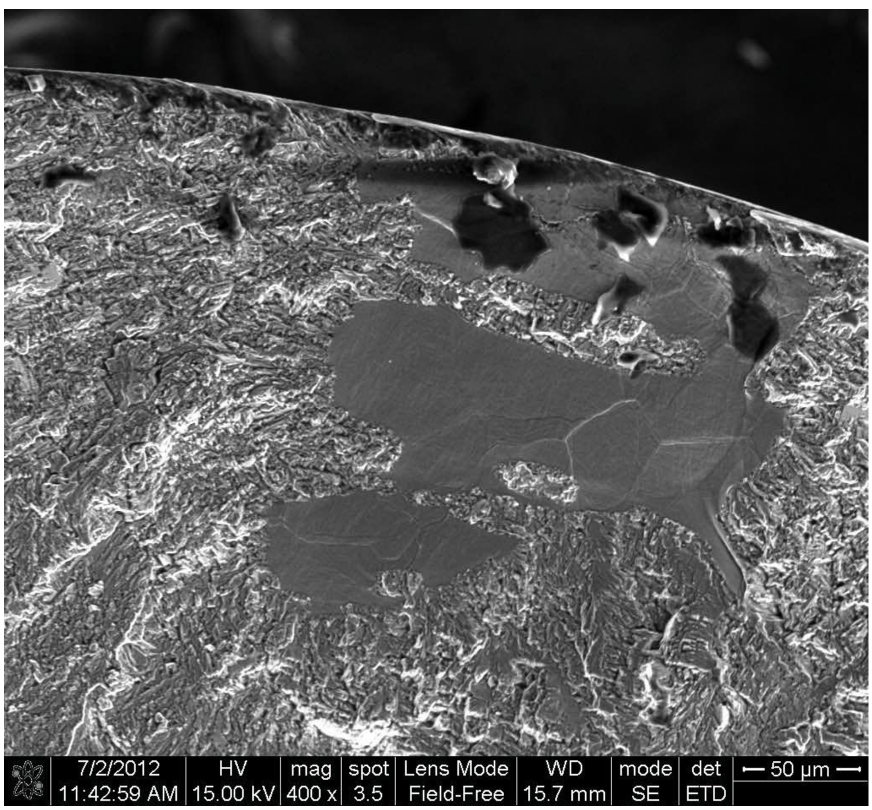


Fig.6. SEM image showing brittle mode of crack initiation for a machined part

Among the different characteristic microstructures exhibited by Ti64 under different processing conditions, lamellar structures are more prone to crack initiation as compared to equiaxed or bi-modal structures. But for crack propagation, lamellar structure offers greater resistance to crack growth than equiaxed structures. In high cycle fatigue, crack initiation forms the major part of the fatigue life and hence extending the crack initiation period will result in higher fatigue life. Therefore, the lamellar microstructure could be the reason for the lower fatigue strength of machined EBM samples as compared to the fatigue strength of standard Ti64 material (machined from wrought and cast material) [7]. The fatigue properties can be further improved by subjecting the as-built samples to Hot Isostatic Pressing [8].

Conclusion

A study on the tensile and fatigue properties of Ti64 samples fabricated using the EBM process in both vertical and horizontal orientations provides the following key observations:

1. Parts built in a horizontal orientation have slightly better tensile properties than parts built in a vertical orientation. Tensile properties of both orientations are comparable to standard Ti64 material.
2. A refined lamellar alpha structure resulted in higher strength.
3. The fatigue strength of as-built specimens in a vertical orientation are inferior to samples built in a horizontal orientation due to the differences in surface conditions
4. The fatigue strength of machined specimens built in a vertical orientation is better than samples built in a horizontal orientation due to the difference in grain orientation.
5. The fatigue strength of machined specimens is significantly better than that of as-built specimens.
6. The fatigue strength of EBM built samples is less than that of standard Ti64 materials

Acknowledgements

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