Mechanical, Corrosion, and Biological Behaviour of Additively Manufactured Ti-6Al-4V Alloy

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By

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Chapter 7 Conclusions and Future Scopes

As discussed in previous chapters related to introduction, literature review, results, and discussion on mechanical, corrosion, and biological behaviour of additively manufactured Ti-6Al-4V alloy, following conclusions and future scopes have been drawn in this chapter.

7.1 Conclusions

7.1.1 Microstructure and Mechanical Properties of Additively Manufactured Ti-6Al-4V Alloy

In this work, samples were built by L-PBF process to check the microstructure and mechanical properties in different conditions, in different build orientations. After additive manufacturing, the components have been heat-treated to relieve the residual stresses induced during fabrication. The mechanical properties of different build-oriented tensile samples have been studied and analyzed with respect to their density, hardness, residual stress, and microstructure. Following are the salient outcomes of the study:

- The orientation of build component affects the UTS and elongation at fracture of the L-PBF Ti-6Al-4V. Tensile specimens with a 0° build orientation demonstrated good tensile strength of 1202 MPa under as-built (AB) types. However, elongation was reduced due to the presence of fine acicular α' martensite. Samples with a 90° build orientation showed the largest elongation (8.04 %) at fracture.
- The heat treatment modified the phase composition of the as-built components and also influenced the tensile behaviour. After additive manufacturing, the α′ martensitic phase forms and that transforms into α and β phases during heat treatment. Hence, 0°

build orientation tensile specimens showed the highest tensile strength of 1081 MPa and the largest elongation at fracture (10.8%). After heat treatment, slip could transfer across the interface of the α and β phases, and the ductility was increased.

- High residual stresses, the maximum in the 90º oriented component, are induced in the as-built condition. Heat treatment is needed to avoid any distortion in the components.
- The highest micro-hardness was observed in the 0° build-oriented AB sample; and lowest in the 90° build orientation. After heat treatment, the micro-hardness was reduced due to microstructure coarsening and transformation of α′ martensite into a mixture of α and β phases.
- Fracture behaviour was also affected by the build orientations and was dependent on the growth direction of the microstructure. The interlayer pores and the presence of residual stress contributed to crack initiation and propagation. Heat treatment mitigates the effect of the residual stresses.

7.1.2 Surface Characteristics of Additively Manufactured Ti-6Al-4V Alloy

The additively manufactured Ti-6Al-4V samples have been finished using surface abrasive grinding at different DOC and table speeds in different environments. Various outputs like grinding force, temperature, surface roughness, microhardness, and SGE have been investigated, and the findings are summarized below:

- Cryogenic grinding contributed significantly to reduction of grinding forces and heat produced in the grinding area, thereby surface roughness was less compared to that from dry and wet grinding. In cryogenic grinding, the tangential forces were reduced by 57.14% as compared to dry and approx. 50% with respect to wet conditions, and for normal forces, the reduction was approx. 50% with respect to dry and approx. 33.33% as compared to wet grinding for the maximum DOC and table speed.

- The heat developed during cryogenic grinding was about 55% and 68.92% less than that from dry grinding at a minimum and maximum DOC and table speed, respectively.
- The R_a value of the finished L-PBF samples was decreased from 5.94 µm to 0.356 µm, 0.337 µm, and 0.259 µm and according to 3D atomic force micrographs, the S_a values were measured as 229 nm, 164.3 nm, and 137 nm in dry, wet, and cryo environments, respectively.
- Surface roughness was improved in cryogenic grinding because of low grinding zone temperature and it was reduced by 27.25% and 23.15% for the AM and 30.08% and 29.13% for the conventional samples in comparison with dry and moist conditions, respectively. Also, it was observed that finished AM Ti-6Al-4V samples had better surfaces than finished conventional samples. The finished surfaces were also analyzed by atomic force microscopy, and it was found that the surface roughness was achieved to be 229 nm, 164 nm, and 155 nm for the finished AM and 273 nm, 195 nm, and 173 nm for the finished conventional samples in dry, moist, and cryogenic conditions, respectively.
- The subsurface layer shows a significant difference as a function of grinding environmental conditions. Grinding of the surface alters the microstructure in the subsurface layer. The subsurface layers, below the finished surface up to depth shows ~20 µm, smaller α grains and β grains were almost diminished. The smallest grains were observed under cryogenic finishing conditions, compared to dry and moist finishing because of the constraint in grain growth at low grinding

temperatures. Due to this, cryogenic finishing produces harder and stronger surfaces as compared to dry and moist finishing.

- Initially, the microhardness of the as-fabricated AM Ti-6Al-4V samples was measured as 427.806 ± 20 $HV_{0.2}$. The microhardness varied from 432.81 to 488 $HV_{0.2}$, 449.39 to 488.71 $HV_{0.2}$, and 450.17 to 502.85 $HV_{0.2}$ at the minimum and maximum DOC and table speed in dry, wet, and cryo environments.
- Suggested values of DOC and table feed for the conventional Ti-6Al-4V alloy were used for finishing the AM Ti-6Al-4V specimens. The positive surface roughness results highlight that the above set of DOC and table feed can be used even when L-PBF Ti-6Al-4V components are subjected to finishing operations, to enhance the surface quality.

7.1.3 Corrosion Behaviour of Additively Manufactured Ti-6Al-4V Alloy

The electrochemical response of the additively manufactured Ti-6Al-4V samples has been evaluated to study the role of the build orientation and HT process. Concluding remarks are as follow:

- Fast solidification during the L-PBF process and the formation of martensitic α' phase degraded corrosion resistance of the AB samples as per the results shown by Tafel curves. These findings have been further supported by the EIS test, which showed that the AB samples have a less effective passive protective layer than that resulting from the HT.
- The Tafel curve confirmed that HT samples show superior corrosion resistance than the AB samples because of having α+β phases in the microstructure, following the HT.

- The EIS results show that in the HT samples the charge transfer resistance (R_{ct} = 310130 Ω.cm^2) was higher than that of AB samples (R_{ct} = 98096 Ω.cm^2). It indicates that the oxide layer thickened due to HT.
- The corrosion rate decreases when build orientation increases from 0° to 90° in as-built condition. The AM AB-0° oriented samples exhibit lower corrosion resistance due to finer acicular martensitic phase than AM 45° and 90° samples. The corrosion rate of Ti-6Al-4V samples after heat treatment is comparable with that of conventionally manufactured Ti-6Al-4V samples.
- For AM 45° samples, the arc curvature of heat-treated samples was found to be lower than the as-built samples, because the distribution of grain size in 45° oriented samples is still fine.
- The AM HT samples had higher R_s values than the AM AB samples, but for the conventional samples, the AB samples had higher R_s values than the HT sample. The R_{ct} values of HT-45° samples were about 1.3 times and 1.7 times those of HT-0° and HT-90° samples, respectively.

The Tafel curves and EIS results confirmed that Ti-6Al-4V samples fabricated by the L-PBF process in different orientations and heat treated exhibit minimal corrosion as compared to the as-built L-PBF samples.

7.1.4 Wear and Biological Behaviour of Additively Manufactured Ti-6Al-4V Alloy

This investigation involved subjecting the L-PBF and conventional Ti-6l-4V alloy to wear tests across various orientations relative to the normal loads and sliding velocities. The wear analysis aimed to explain the wear properties and fracture mechanisms while emphasizing the influence of build orientation. Several conclusive findings emerge from this study:

- With an increase in the applied load, there is an increase in wear depth, consequently volumetric wear is increased. Across all samples, except for the as-built L-PBF 0° sample, wear depth reaches its peak at 25 N and 382 rpm. However, the aforementioned L-PBF 0° sample exhibits its maximum wear depth under 25 N and 891 rpm. The wear tracks of the conventional and L-PBF AB samples are rougher than that of L-PBF HT samples.
- The wear rates exhibited by the heat-treated samples were comparatively lower than those of their as-built counterparts, due to improved wear resistance. Post heat treatment wear rates of L-PBF samples is comparable with those of conventional samples. At low loads and sliding velocities, the maximum wear rate occurs in the 90° orientation, followed by the 0° orientation, while the 45° orientated sample demonstrates the minimum wear rate. This trend alters at higher loads and sliding velocities, showing a change in the wear rate sequence across orientations.
- Following heat treatment, as build orientation increases from 0° to 90°, initially the wear rate of L-PBF samples increases then decreases across load and sliding velocity conditions. The coefficient of friction of the heat-treated samples was comparatively higher than those of their as-built counterparts.
- The AB 45° worn samples show evidence of deep grooves, abrasive wear, oxidized particles at each load and sliding velocity. At high load and sliding velocity, the AB 45° sample shows significant transfer of zirconia on the Ti-6Al-4V samples, it was confirmed by the presence of zirconia weight % in elemental

distribution map. The AB 90° worn samples show the presence of delamination, grooves, and oxidized particles at each load and sliding velocity.

- For conventional samples, more oxide layers are formed at 5 N load and 891 rpm sliding velocity in comparison with other load and sliding velocity conditions. Same trend is observed for the L-PBF as-built 0° oriented samples, but minimum oxide layer is formed at 25 N load and 382 rpm sliding velocity. In most of the samples, minimum oxide layers are formed at 25 N load and 382 rpm sliding velocity except in the conventional and L-PBF HT-90° samples.
- The surface roughness of L-PBF Ti-6Al-4V samples can have a significant impact on cell culture in context of biomedical applications. In the as-built samples, more cells are adhered on 45° oriented samples, followed by 0°, and minimum cells are adhered on 90° oriented samples. After heat treatment, maximum cells are adhered on 45° oriented samples, followed by 90°, and minimum cells are adhered on 0° oriented samples.

It can conclude that the formation of surface oxide is more dominant on the wear resistance than that of microhardness of the sample. These results suggest a complex interplay between build orientation, applied load, and sliding velocity. Additionally, surface roughness plays a crucial role in cell adhesion and proliferation.

7.2 Future scopes

This study highlights the impact of build orientation and heat treatment on the mechanical properties of additively manufactured Ti-6Al-4V alloy, with an emphasis on its suitability for biomedical applications where it is critical for mimicking the elastic modulus of bone material. The AM process provides control over porosity levels, which makes it easier to modify the elastic modulus of the alloy to match with elastic modulus of bone material.

Furthermore, comprehensive biological assessments, including cell culture growth, are necessary to determine the biocompatibility and bioactivity of the AM Ti-6Al-4V samples.

In this study, samples built with 0° orientation provided the best properties amongst the three orientations. However, a rigorous study is needed to establish optimum build orientation. It is an experimental study that needs to be supplemented by modelling and simulation for getting better insight of the process. This study also highlights the need for optimization of the build orientation and heat treatment to improve the corrosion resistance of the additively manufactured Ti-6Al-4V alloy. It is an experimental study that needs to be supplemented by exploring various surface treatments or coatings to minimize corrosion and improve the alloy's long-term performance.