Tribological analysis of wire additive manufactured Ti6Al4V by Electron Beam source

Manjunath A (manjunathgtre@gmail.com)  
Gas Turbine Research Establishment

Anandakrishnan V  
Gas Turbine Research Establishment

Ramachandra S  
Gas Turbine Research Establishment

Parthiban K  
Gas Turbine Research Establishment

Sathish S  
Gas Turbine Research Establishment

Original Research Full Papers

Keywords: Additive manufacturing, Wire Electron Beam, Dry sliding wear, Wear mechanisms

DOI: https://doi.org/10.21203/rs.3.rs-194129/v1

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Abstract

Additive manufacturing through electron beam, is an attractive and fast growing additive manufacturing process for complex geometry in the aerospace, automotive and rapid tooling industry. Ti6Al4V is the material which is widely used in aerospace industry owing to its good strength-to-weight ratio, higher strength and toughness and admirable corrosion resistance. Ti6Al4V samples were realized through wire electron beam additive manufacturing by Pre-positioning the wire and then fusing it to the substrate material. The samples were subjected to standard dry sliding wear test to explore the wear behaviour. The wear analysis exposed the substantial effects of parameters on the wear rate. Likewise, the mechanisms that significantly influenced the wear rate was identified with worn surface and debris analysis.

1 Introduction

Material is the heart of engineering and based on its application, it is choosen to meet the product requirements and it functionalities. Based on the property, quantity, features, complexities and economics of product the suitability of process of manufacturing a material is identified. Though plenty of techniques were there to realize a material, the thirst of finding a newer methodology is still not quenched. In that line, additive manufacturing gives an insight with freedom for design and manufacturing engineers [1]. Wire based Electron Beam Additive Manufacturing (EBAM) is an advanced method wherein the wire is fed in line with the beam of electrons, which make the wire to melt and gets deposited on substrate. The electron beam is most suited for the process as it has good control and better penetration [2]. Also, the high vacuum of 10⁻⁴ mbar in the work chamber provides protection against the contamination from the atmosphere. Especially, it is suitable for reactive materials such as titanium alloys which is extensively used in the aircraft components, automotive components and biomedical components [3, 4]. Though the titanium alloys are made ready in different forms such as cast, wrought, and powder sintered [5], realized through casting, and powder metallurgy, additive manufacturing is one more added with that owing to its merits. Neikter et al. produced the titanium alloy Ti6Al4V through two different additive manufacturing process (EBM and SLM) and detailed the microstructural characterization of the produced alloy [6]. Galarraga et al. made the Ti-6Al-4V alloy through the process of electron beam melting and further heat treated and observed the formation of α'martensite due to faster rate of cooling [7]. Yang et al. produced the Ti-6Al-4V alloy through the process of selective laser melting and studied the variations in the formation of α and β phase with respect to the variation in holding temperatures [8]. With the electron beam melting technique, different aerospace parts were fabricated with Ti-6Al-4V alloy and found its metallurgical and mechanical properties are equivalent to the bulk materials [9]. The wear performance of Ti-6Al-4V alloy was studied under lubricated condition and observed that an increased sliding velocity marks in the reduction of wear [10]. The tribological analysis of Ti-6Al-4V alloy was studied under varied load and sliding velocity with dry condition and observed the wear reduction with increased load and sliding velocity [11]. The wear performance of Ti-6Al-4V alloy was studied under dry sliding state and observed a remarkable transition in the wear mechanisms with respect to sliding velocity [12].
investigated with different parameter and observed a shearing of material with the increased load [13]. The wear performance of Ti-6Al-4V alloy sintered through selective laser melting was studied under lubricated condition and the results showed the occurrence of abrasion, oxidation, and delamination mechanism [14]. The literature visibly briefs the earlier attempts of producing titanium Ti-6Al-4V alloy with the additive manufacturing technique and there is no attempt made through the Wire based Electron Beam Additive Manufacturing. It is observed that the Ti-6Al-4V grouped under grade 5 exhibits a poor wear resistance and the alloy has an intended application in the different industries namely aerospace, defence, medical, automobile, marine and in sports equipment [15]. In particular, bearings of heavy duty vehicles, disc brakes, rotors and orthopedics application needs many needs an improved wear resistance of titanium alloy [11, 16, 17]. The titanium alloy is fabricated through additive manufacturing by prepositioned Ti-6Al-4V wires under different parameters and their influence on the geometry of beads are investigated [18]. The structural parts in automobile, and aerospace, sports equipment and medical applications needs an improvement in wear resistance and understanding of wear behavior under sliding conditions. Hence the present research is focus on the development of Ti-6Al-4V alloy through Wire based Electron Beam Additive Manufacturing technique and further to investigate its wear characteristics under dry ambient condition.

2 Experimental Details

2.1 Wire additive manufacturing

Electron Beam Additive manufacturing (EBAM) methodology was employed to synthesis the titanium alloy (Ti-6Al-4V) with the pre-positioned wire. Fig. 1 shows the schematic layout of EBAM setup with pre-positioned wire which used to synthesize the titanium alloy. The electron beam welding machine of make of Cambridge Vacuum Engineering is used to synthesize the titanium alloy. The titanium alloy filler wire of dimension 2 mm in diameter and the substrate of dimension 100 x 100 x 20 mm is used and its respective chemical composition are shown in Table 1. With resistance welding, the filler wire was pre-positioned over the substrate of same titanium alloy and the beam of electrons were focused over the prepositioned wire under vacuum environment of 2x10^{-4} mbar. Thereby the prepositioned wire is melted and gets deposited on the substrate as similar to the process of Direct Metal Deposition process. Three combinations of experiments were attempted by setting 140 kV accelerating voltage, 600 mm/min welding speed and at three variations in beam current (6, 8 and 10 mA). The samples made with the combination of 140 kV accelerating voltage, 600 mm/min welding speed and 8 mA beam current exhibits complete fusion over the substrate, whereas in other two combinations the fusion is observed at the substrate and noticed a drop through. With the optimal combination and aforesaid procedures, the titanium alloy samples of 7.8 mm width, 7.5 mm height and 100 mm length was made, with 30 successive fusion of prepositioned wire one over the other as required. The extracted deposited layer was parted for metallurgical analysis and also turned to produce the wear test samples of size 6mm diameter and 25mm length. The extracted deposited layer was exposed in Rigaku Ultima III diffraction machine to
obtain the diffraction peaks and Vega 3 Tescan scanning electron microscope to sightsee surface morphology.

2.2 Wear experimentation

The wear pins obtained through wire additive manufacturing process were polished at its ends by following the standard procedure. Then the pins underwent the wear experiment in the dry sliding condition as per ASTM G99, in pin-on-disc equipment. The hardened D3 steel is used as the counterpart material for the dry sliding wear test. The merits of performing the experiments in pin-on-disc equipment is a simple and effective technique to evaluate the material wear in a non-abrasive sliding condition. By considering the parameters load, sliding velocity and sliding distance, the wear experiments were conducted for 3000 m sliding distance at varied sets of load (i.e., 9.81, 19.62 and 29.43 N) and sliding velocity (i.e., 1, 2 and 3 ms\(^{-1}\))[12,19–23]. Upon the accomplishment of wear experiments, the amount of material worn is identified with the linear wear, is further transformed to general form wear rate using the expression (1)[24].

\[
Wear\ rate, \ mm^3 m^{-1} = \frac{\left(\frac{\pi}{4}\times Diameter\ of\ pin^2\times Linear\ wear\ in\ pin\right)}{Sliding\ distance}
\]  

(1)

3 Results And Discussion

3.1 Metallurgy of additive manufactured titanium alloy

To examine and compare the phase existence in the additive manufactured titanium alloy with the base titanium alloy, both the materials were x-ray diffracted and the results were plotted as shown in Fig. 2. The diffraction obtained for the base material match with the reference pattern 98-008-0571 exhibits the alpha titanium with (hkl) indices of (002), (011), (012), and (013). The diffraction obtained for the additive processed material match with the reference pattern 98-009-2053 exhibits the titanium with (hkl) indices of (010), (002), (011), (012), and (013). The observed peak intensities of the additive manufactured sample is found to increase compared to the base material and this is due to the modification of material structure as observed in Fig. 3. Fig. 3 shows the microstructure of base titanium alloy and additive manufactured titanium alloy. The base titanium alloy exhibits the equiaxed alpha and beta structure and the additive titanium alloy exhibits the needle shaped acicular a phase(elongated structure) with the transformation of beta due to rapid cooling of material [5].

3.2 Wear performance

The additive manufactured titanium alloy exposed to dry sliding wear exhibited the wear rate as shown in Fig. 4. The exhibited wear rate of titanium alloy under 1 ms\(^{-1}\) sliding velocity at varied loads are depicted in Fig. 4a, the wear rate of additive manufactured titanium alloy shows a lower wear rate at lower load of 9.81 N and it exhibits a higher wear rate at medium load of 19.62 N. When the load was at higher level
i.e., 29.43 N, it exhibits an intermediate wear rate between the lower and higher condition. The wear rate is found to be in steady state after 1500 m sliding for the higher and medium loads, whereas at lower load it is achieved after 2500 m sliding distance. This is due to the higher frictional force acting on the sliding surface at higher loads results in the reduction of asperity to asperity contact. Similar trend of wear rate was perceived in the additive manufactured titanium under 2 ms\(^{-1}\) sliding velocity. But the reduction of wear is clearly visible after the 1500 m sliding distance at medium and higher load, which is resulted from the oxidation mechanism, at increased sliding velocity and load. Whereas at lower load, there is no such declining trend, this shows there is no enough amount of frictional force and temperature to induce the oxidation formation. Though the wear rate of titanium alloy at 3 ms\(^{-1}\) seems to be similar like 1 ms\(^{-1}\) and 2 ms\(^{-1}\), the wear rate at lower and medium load is found to be increased at the initial run and it is declined up to the sliding distance of 1000 m. The possible effect for this reduction are the surface oxidation of the contact asperities at the initial run period due to higher contact stress. Beyond 1000 m sliding distance, it showed an increasing trend of wear rate and it is due to the removal of oxidized asperities from the pin surface. Almost in all the velocities, higher load exhibited higher wear rate and drop in load results in reduction in wear rate. Initially the wear rate seems to be lower at the lower sliding velocity and it found to be increasing with the increase in sliding velocity to 2 ms\(^{-1}\). Further, the increase in sliding velocity decreased the wear rate, and this is attributed due to the mechanism of oxidation. Similar trend of reduction in wear rate with an increased sliding velocity and increased wear rate with increased load is reported by Straffelini and Molinari[25]. The comparison of wear results with the base material under different working conditions are presented in Table 2, which shows that the additive manufacture sample has better wear resistance compared with the base alloy.

The additive manufactured titanium alloy exposed to dry sliding wear exhibited the coefficient of friction as shown in Fig. 5. The exhibited coefficient of friction of the titanium alloy under 1 ms\(^{-1}\) sliding velocity at varied loads are shown in Fig. 5a. It shows that higher coefficient of friction at higher load and it got reduced with the reduction in load. Also, there is a slight fluctuation in the coefficient of friction and this is due to the variation in the surface topography during sliding. Similar trend was observed under sliding velocity of 3 ms\(^{-1}\), whereas for sliding velocity of 2 ms\(^{-1}\), the coefficient of friction is higher for medium load for 19.62 N load. The possible reason for this is at sliding velocity 3 ms\(^{-1}\), oxidation occurs, that leads to the reduction in coefficient of friction as the oxide layer acts as lubricant. Also, the coefficient of friction is found to be reduced with the increase in sliding velocity and this effect is due to the formation of oxide layer.

3.3 Wear mechanism

The dry sliding of titanium alloy pin results in the destruction of sliding surface, which helps to reveal the involved wear mechanism. After dry sliding, the pin which exhibits the best wear rate and worst wear rate was analysed under scanning electron microscope as shown in Fig. 6. The surface topography of wear pin corresponds to the worst wear (i.e., load of 29.43 N with sliding velocity of 2 ms\(^{-1}\)) in Fig. 6a, it shows the presence of crater, scratches, and spalling that evident the delamination, and abrasion mechanism.
The observation of fragment and laminates confirms the mechanism of delamination and abrasion from Fig. 7a. The topography of wear pin surface corresponds to the best wear (i.e., load of 9.81 N with sliding velocity of 3 ms\(^{-1}\)) is shown in Fig. 6b, with spalling, ridges, shallow crater, ploughs, and scratches. The ridges on observed surface morphology raised due to the deformation of deformed layers due to adhesion and the ploughs and scratches evident abrasion mechanism. The observation of ribbon flakes, laminates, and fine debris confirms the mechanism of delamination, abrasion and oxidation from Fig. 7b. The mechanism of oxidation is confirmed with the presence of oxygen content in the worn pin corresponds to the best wear condition.

4 Conclusion

Ti6Al4V alloy was produced through additive manufacturing using Electron Beam with pre-positioned wire and its metallurgy was analysed. The additive manufacture titanium alloy exhibits a needle shaped acicular \(\alpha\) phase due to the rapid cooling. The wear analysis showed the increased rate of wear with an increased load and the increased sliding velocity exhibits a reduction in wear rate. Also it was noticed that the rate of wear is increased initially and then it reduced at medium sliding velocity with high and medium loads. The investigation on the worn surface under the microscopic level exhibit the surface topographies with crater, ploughs, scratches, white patches and spalling, manifest the delamination, adhesion, oxidation and abrasion mechanism. Similarly, the collected debris exhibit the laminates, ribbon fragments, and fine debris confirms the above delamination, adhesion, oxidation and abrasion mechanism.

Declarations

**Funding:** There is no resource of funding for the present work.

**Conflicts of interest/Competing interests:** There is no conflict of interest for the authors.

**Availability of data and material:** Not applicable

**Code availability:** Not applicable

**Authors' contributions:** All the authors have their contribution in the concept, design, characterization, analysis, and manuscript preparation.

**Consent to participate:** Not applicable

**Consent for publication:** All the authors agreed their consent for publication

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Tables

**Table 1. Chemical composition of titanium alloy**

| Material      | Al | Va | C  | N  | O  | H   | Fe | Y  | Ti  |
|---------------|----|----|----|----|----|-----|----|----|-----|
| Substrate - Ti6Al4V | 6.0 | 4.0 | 0.10 | 0.05 | 0.20 | 0.012 | 0.30 | -  | Balance |
| Wire - ERTi6Al4V   | 6.7 | 4.5 | 0.05 | 0.03 | 0.18 | 0.015 | 0.30 | 0.005 | Balance |
Table 2. Comparison of wear rate of titanium alloy

| S. No | Load, N | Sliding Velocity, m/s | Sliding Distance, m | Wear rate mm$^3$m$^{-1}$ |
|-------|---------|-----------------------|---------------------|--------------------------|
|       |         |                       |                     | Additive Ti6Al4V         | Base Ti6Al4V              |
| 1     | 9.81    | 1                     | 3000                | 0.001670                 | 0.001739                 |
| 2     | 9.81    | 2                     | 3000                | 0.002664                 | 0.002035                 |
| 3     | 9.81    | 3                     | 3000                | 0.000164                 | 0.000932                 |
| 4     | 19.62   | 1                     | 3000                | 0.003789                 | 0.003875                 |
| 5     | 19.62   | 2                     | 3000                | 0.007035                 | 0.004834                 |
| 6     | 19.62   | 3                     | 3000                | 0.000627                 | 0.002835                 |
| 7     | 29.43   | 1                     | 3000                | 0.006887                 | 0.007052                 |
| 8     | 29.43   | 2                     | 3000                | 0.009608                 | 0.010128                 |
| 9     | 29.43   | 3                     | 3000                | 0.004550                 | 0.003655                 |