A Review Article: The Mechanical Properties and the Microstructural Behaviour of Laser Metal Deposited Ti-6Al-4V and TiC Composite

Mutiu F. Erinosho[a*], Esther T. Akinlabi[a],

[a]Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park Kingsway Campus, Johannesburg, 2006, South Africa.

Corresponding author: mferinosho@uj.ac.za, +27747425924

ABSTRACT

Titanium alloys (Ti6Al4V) Grade 5 have been regarded as the most useful alloys for the aerospace applications, due to their light weight properties. Today, laser technology is an energetic process in which the beam ejected can travel a longer distance and spot on the focused surface. The combination of metallic powder and laser beam has been used concurrently to form a solid figure. However, this combination has generated a permanently solidified adhesive bonding between the laser-deposited metallic powders. Several research works have been conducted to improve the mechanical properties of the primary alloy. This article conversely highlights the series of work that have been conducted on improving the mechanical properties and microstructures of the primary alloy with the addition of titanium carbide (TiC). The Ti-6Al-4V alloy has been widely selected in most critical part of a component. Their reinforcement with TiC composite particle has been achieved successfully through the optimal usage of laser technology. The characteristics of the reinforced component have vehemently improved the mechanical properties such as the tensile strength, wear resistance, fracture toughness and hardness; as well as the morphologies and phases of the microstructures.

Keywords: Application, Laser technology, mechanical properties, microstructure, Ti-6Al-4V, Titanium carbide

1. INTRODUCTION

Titanium and the functionally graded alloy materials have been widely investigated to improve the properties of the composite in different applications. Today so many components have gained ground with the use of titanium alloy. Such as the aircraft industries, automobile, sports, biomedical and some chemical and petroleum industries.Ti-6Al-4V is most applicable among the titanium alloys since it exhibits a combination of mechanical, physical and corrosion resistance which have made them desirable for demanding in aerospace, industrial, chemical, energy and automotive industrial services. They are also applied in the emerging biomedical prostheses applications due to the excellent biocompatibility among metallic materials [1-2].

Today engineers and the researchers look for ways to modify the surface integrity of Ti-6Al-4V and look for ways to improve the parts of component concern in other to enhance the development in the advance technology of the Ti-6Al-4V since it is the most useful alloy applicable today. The alloy is reinforced with Titanium carbide (TiC) to cause an improvement in the surface modification. Many researchers have contributed immensely in this development in terms of the microstructural improvement, wear resistance modification, improve hardness and many more. Literatures have proven the reinforcement of titanium and TiC composite provide a better surface modification [3].

However, about a decade ago the Direct Laser Fabrication (DLF) which is a novel manufacturing technique can directly fabricate 3D near net shape and fully dense components from metal powders in one step [4, 5]. The principle behind the net

shape technology is the stereo lithography features and the laser which is controlled by the computer-aided design profile during the operation.
During fabrication, the reinforced mixture powder is fed and delivered into the gas stream and directed towards the substrate at a controlled rate from the focal point of a laser. The movement of the laser follows the path defined by the CAD component profile and melts the powder mixtures on the substrate. A small molten pool was generated on the substrate and the powdered particles are injected directly into the melt pool via a powder feeder. As the laser beam moves away from the substrate, the molten pool solidifies rapidly, forming a thin layer of welded metal to the material. Adversely, an overlapping layer is formed repeatedly and completely on the substrate. The deposition process occurs inside an enclosed chamber to prevent oxidation of the liquid metal from the atmosphere. DLF techniques are useful in verifying the influence of changes in the composition by varying the fraction of two fed powders simultaneously into the focal point of the laser. This approach leads to a low capture rate of the powders and causes a wastage of the scattered powder since the fraction of the two powders will be mixed with each other. The use of premixed powders is an alternative approach [6], but the difficulty of ensuring that the two mixed powders do not segregate during gas-assisted feeding to the laser. Liu and DuPont produced functionally graded Ti/TiC composite deposits using the Laser Engineered Net Shaping (LENS) process and employing separate powder feeders for introducing Ti and TiC powers in desired quantities. [7] Due to thermal stresses, solid-state cracking of TiC/TiAl composites was prevented during fabrication using preheated titanium substrates [8].
This reviewed article shows the series of work that have carried out by different researchers on the improvement on the surface modification of Ti6Al4V/TiC during Laser Metal Deposition.

2. MECHANICAL PROPERTIES OF THE REINFORCED Ti-6Al-4V/TiC

2.1. Tensile test analysis

Wang et al conduct some experiments with 0.45mm diameter wire feed Ti–6Al–4V and 99.5% purity powder feed TiC ROFIN SINAR TRIAGON 1750W CO_2 laser powered at 1148W and a scan speed of 150 mm/min was used throughout the experiment in an oxygen controlled atmosphere below 10ppm.both the materials was laser melt separately on a 20mm thick plate hot rolled Ti–6Al–4V substrate. Tensile test was conducted after heat treating for 2hours at 600 ◦C in an argon atmosphere. The plates were thermally stress relieved by heat treating for 2 h at 600 ◦C in an argon atmosphere and 4 hours at 930 ºC for hot isostatically pressed with a pressure of 103MPa. The result shows that at room temperature, annealed and hot isostatically pressed condition, the yield strength, tensile strength and modulus of elasticity of the reinforced component is superior to the direct laser fed Ti-6Al-4V but a decrease in ductility [9].
Da silva et al carries out an investigation on Ti6Al4V matrix reinforced with 10 wt% of TiC particles both at room and hot isostatic pressing temperature which was produced by the BE-CHIP method. Tensile tests were carried out at room temperature on a rod (6 mm diameter and 30 mm gauge length) in a Zwick 1484 testing machine with 0.2 mm/min displacement rate [10, 11] and at high temperature performed at 200 and 375 ºC in a Schenk Trebel RM100 testing machine [11,12]
At room temperature, there is an increase in both the tensile and yield strength value of the based material compared to the parent matrix which is due to the much higher work-hardening rate at lower strains by the elastic reinforcing particles on the plastic flow of the matrix and result in the reduction of the ductility of the materials.
At high temperature, the resulting tensile test shows a reduction in both the tensile and yield strength value due to a decrease in density and dislocation rate and this lead to an increase in ductility as a result of resistance loss to plastic deformation [11].
In an experiment conducted by Zheng et al, a matrix powder of Ti-6Al-4V with a size range of 45 to 106 µm was reinforced with 33% Ni-coated TiC particles which were produced through the chemical vapor deposition (CVD) fast fluidized bed process. The reinforced composite Ti-6Al-4V + 20% wt TiC/Ni and Ti-6Al-4V + 10% wt TiC/Ni undergo a compressive test which was done either parallel or vertical to the deposition direction and resulted in the yield strength of 1950 and 1700 MPa, respectively, while that Ti-6Al-4V alloy is 970 MPa. The ductility is relatively low by 2 to 3% for the reinforced

composite. Likewise the tensile test conducted results in the fractural decreases with increasing fraction of TiC/Ni particles which is attributed to the grain size refinement, dislocation density, intermetallic compound and the TiC particle [13].
Huang et al fabricated Ti6Al4V and TiC composite from raw powder materials milled at the speed of 200rpm for 8 h using a planetary blender with low-energy under pure argon
Atmosphere.

The comparison between the compressive yield strength of Ti6Al4V and TiC composite and the monolithic Ti6Al4V alloy of a sintered and heat treated samples was investigated. Figure 1 shows the plot of the yield strength against the sintered and the heat treated samples.

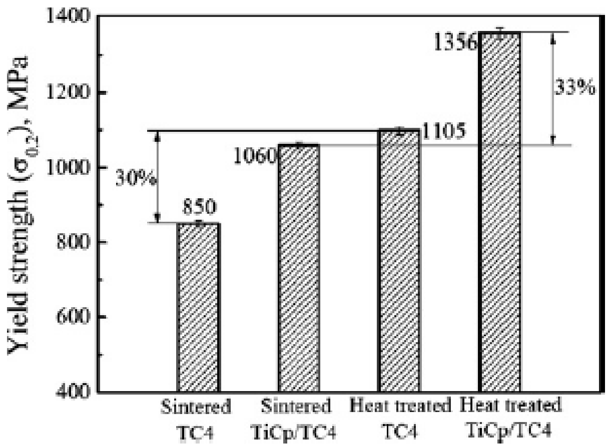


Figure 1. Comparison between the compressive yield strength of the monolithic Ti6Al4V alloy and Ti6Al4V/TiC composite before and after heat-treatment. [14]

With 5 vol.% TiC particles synthesized, the yield strength of the as-sintered composite increased from 850MPa to 1060 MPa. After the heat treatment, the yield strength of the monolithic Ti alloy and composite was increased to 1105MPa and1356 MPa by 30% and 33 % respectively.
30% and 33%, respectively. The variance in the percentage of the yield strength was reported to can be attributed to the equiaxed microstructure of matrix in the composite with a network microstructure.[14]

2.2. Hardness test investigation

Sampedro et al laser clad Ti-6Al-4V and TiC with different concentrations of TiC on Ti-6Al-4V samples. The investigation was done by means of an Nd: YAG laser TRUMPF(HL1006D) with a wavelength of 1064 nm and a maximum output power of 1KW. The hardness Vickers test was carried out on the composite and the result shows that the hardness of the coating is higher than for the base material (135 Hard Vickers), but the heat affected zone (HAZ) has lower hardness due to a lower cooling rate. And concluded generally that the hardness of the samples surface of Ti-6Al-4V was increased and the cooling rate is higher corresponding to a lower specific energy. It was also observed that due to the massive dilution of primary TiC particles in the clad, the microhardness of the clad layer decreases as the specific laser energy increased [15].
Jun et al improved the hardness of a 50 mm diameter and 10 mm long hot rolled Ti-6Al-4V substrate by laser cladding a TiC-TiB reinforced titanium matrix composite coating onto its surface and was carried out using a 5-kW continuous wave

CO2 gas laser with an applied power of 3-3.5kW. The microhardness measurement was performed on a HXD-1000TM microhardness tester with a load of 200g applied for 15 s. A gradient distribution was indicated in the coating and gives a microhardness ranging from HV 875.64 to HV 659.75. The dilution zone at the interface exhibited a microhardness ranging from HV 603.4 to HV 353 and decreases with increasing distance from the coating surface. The microhardness Ti-6Al-4V substrate is HV 330 which resulted in the grain refinement hardening and dispersion hardening of TiC and TiB phases [16].
With the result of Wang et al a gradual increase in the feed rate of TiC powder feed rate, the hardness of the Ti6Al4 was improved effectively [17].
In another experiment conducted by Mahamood et al by varying the scanning velocity on micro hardness and discovered that Ti-6Al-4V substrate has the lowest average microhardness 300 approximate value and at a changed scanning velocity, the microhardness of the reinforced composite increased to about 500 and it's due to rapid solidification of the deposit at higher scanning velocity [18]. Figure 2 shows the plot of the microhardness of the substrate and the deposited samples.

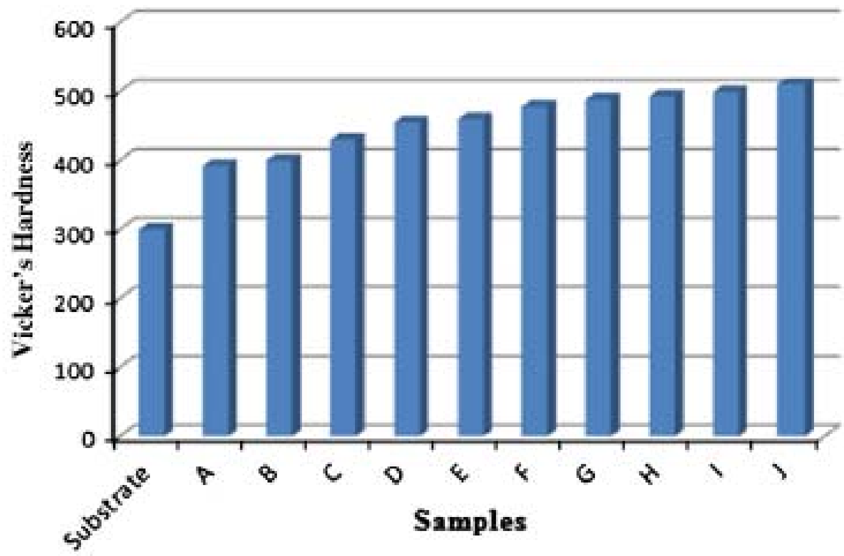


Figure 2: Column of the microhardness of the substrate and the deposited samples [18]

The substrate was revealed to have the lowest average microhardness value of approximately 300 HV. The microhardness values was proportional to the scanning speed. In other words, an increase in the scanning speed leads to an increase in the hardness values. The highest average microhardness of almost 500HV was achieved with samples deposited at the scanning speed of 0.105 m/s. The trend was reported to be ascribed to the rapid solidification of the deposit at higher scanning speed.

Popoola et al in the microhardness behaviour of surface modification of Ti-6Al-4V/Zr-TiC metal matrix composite, a Dura Scan Vickers hardness tester was used for the test; using an indentations load of 100 g for 15 s dwell time. They came to a conclusion that the hardness of the metal Matrix composite increases with an increase in the ceramic powder content [19].
In the *in-situ* synthesized TiB and TiC reinforced titanium matrix composite coating Jun et al measured the fracture toughness of the coating using the Vickers indentation method. A clear and integral indentation occurs except for some fine cracks that were generated at the square angles of the indentations and propagated towards the area far from the indentations. As a result of the elastic modulus between reinforcements and the matrix, deformation occurs. These in turn give rise to stress concentration and cracks propagation. Fracture toughness is increased with an increase in surface distance while the propagation distance of cracks is gradually reduced [16].

However da silva et al observed slight scattering values by the presence of the TiC particles and their distribution as well as the local interparticle spacing, particle diameter and aspect ratio. The crack path of the fracture toughness specimens in the composite is strongly influenced by the TiC particles and its resistance against crack propagation is considerably smaller and crack easily initiates in such locations when there is a homogeneous particle distribution. Da silva et al in their journal quoted Berns et al that a suggested crack deflection leads to an increase of the crack area; thus more surface energy is needed by a deflected crack to propagate than a straight crack path and therefore lead to an improvement of the fracture toughness behaviour [20].

Da silva et al concluded that the fracture mechanism of the fracture toughness specimens is the same to the tensile test observation. In other word, growth followed by ductile fracture of the matrix by coalescence of microvoids. However they have also shown that extensive microcracking at the vicinity of the crack tip indicate the presence of another fracture mechanism due to high local stresses are associated with it. Another characteristic feature that strongly influences the fracture toughness is the reinforcement size since the larger particles has a higher probability of fracturing than the smaller ones [11].

2.3. Wear resistance test behaviour

MT4002 tribometer was used by Sampedro et al in their wear resistant test and result shows that the wear resistance was improved. The dry sliding wear tests was used in comparing the cladded layers to the Ti6Al4V substrate and ultimately the selection leads to an improvement of the wear resistance and thus the friction coefficient increased [15].

In the wear resistance analyses of Jun et al, the coating is strongly attributed to the combination of unique mechanical physical and chemical properties of TiB and TiC reinforcements in the matrix distribution. The strong atomic bond amounts to an excellent abrasive wear resistance due to plowing during dry sliding wear processes [16].

Wang et al assessed the wear properties using a pin-on-disc machine tribometer in which the specimens were rotated against a stationary hardened bearing steel ball of 8 mm diameter at a speed of 66 rpm and the test was carried out with a stylus profilometer in natural air with no lubrication. It was shown that Ti6Al4V without TiC particles signifies a very poor wear resistance. The conclusion was drawn to the evidence that the tribological properties were dramatically improved by the TiC particles involvement [17].

In another experiment conducted by wang et al on the laser fabrication of Ti6Al4V/TiC composites using powder and wire feed concurrently. Tribological characterizations were conducted on the reinforced Ti6Al4V/TiC samples A load of 10 N and sliding distance of 1000 m were taking into consideration. The wear losses were acquired from the resulting parameters. Samples with different volume percentages (Vol %) of TiC in the Ti6Al4V were characterized. Debris and plough grooves were observed in the worn surfaces of the Ti6Al4V without TiC as shown in Figure 3(a).This was reported to occur by the combination of adhesion, abrasion and plastic deformation mechanism[9][18]. Figure 3(b) shows the wear morphology of sample deposited with 24 vol% TiC.

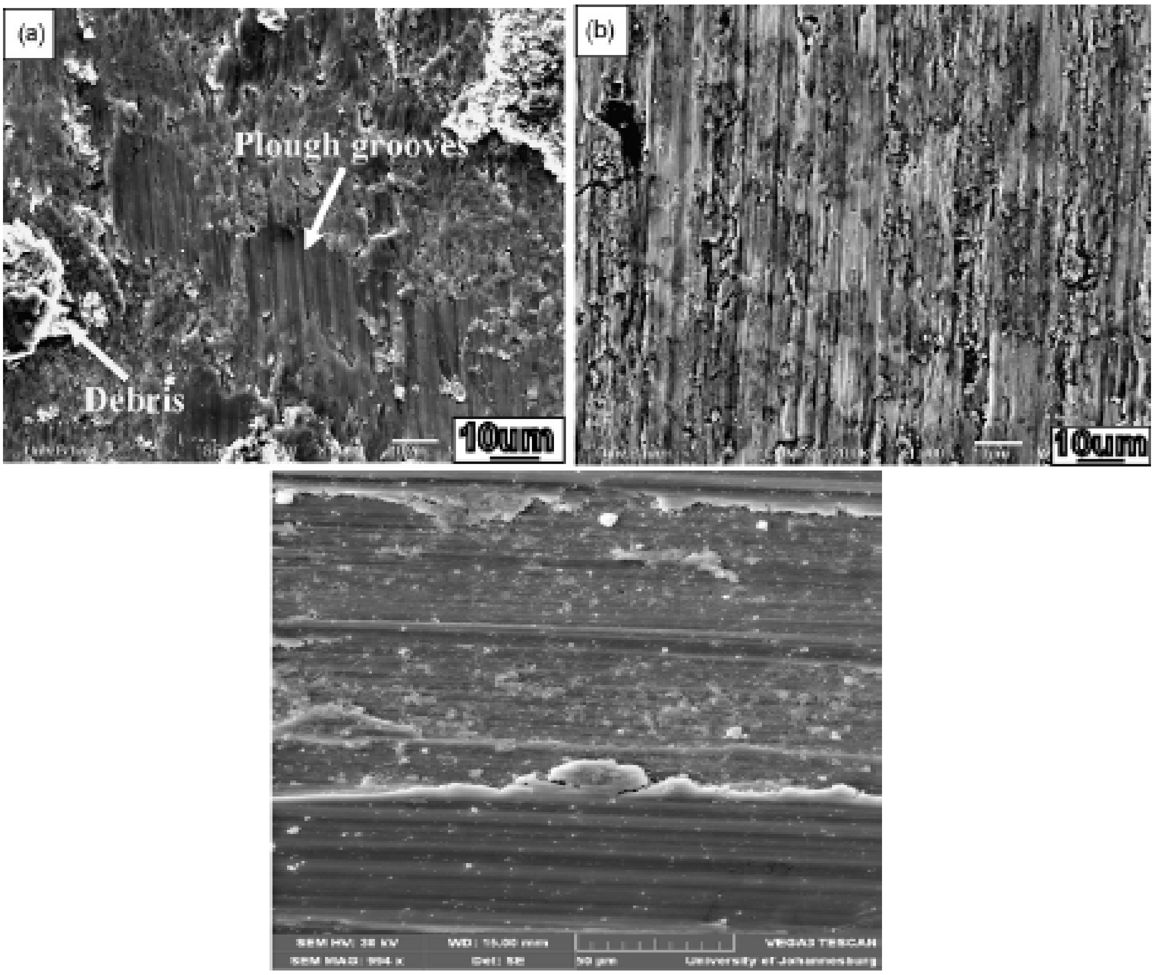
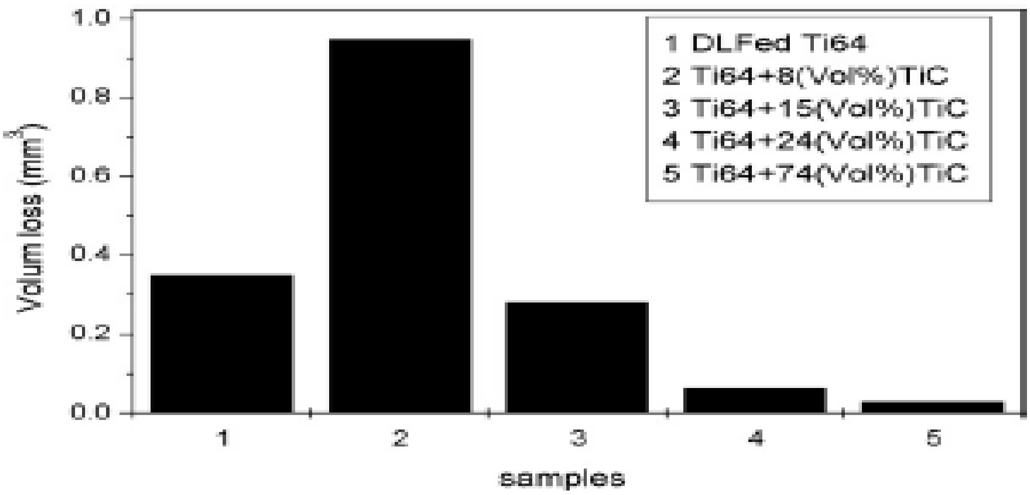
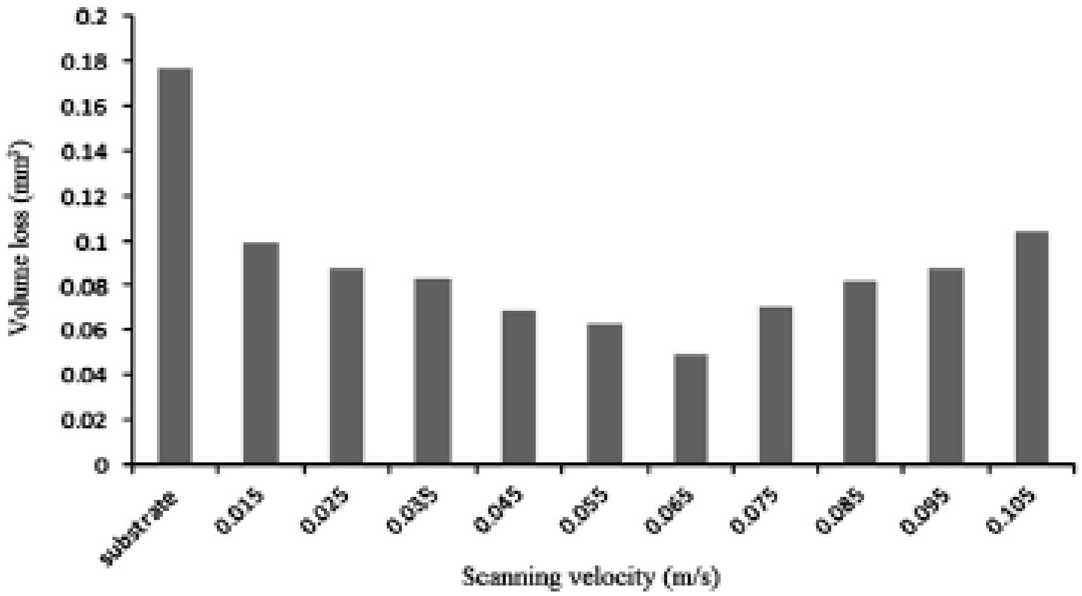


Figure 3: (a) Backscattered electron micrograph of the wear tracks of Ti6Al4V alloy [11]; (b) 24 Vol% of TiC in Ti6Al4V alloy [11]; (c) SEM micrograph of the wear track of the sample deposited at a scanning speed of 0.065 m/s [18]

An increase in the TiC powder feed rate led to the increase in the hardness and the wear behaviour of the reinforced composites. It was also reported that during the sliding process, some rigid particles like TiC were pulled out and attached to the surface of the steel ball surface and act as micro-cutters. Less than 15 vol % TiC was also reported not to improve the sliding-wear resistance of the reinforced samples due the fact that, the TiC precipitated along the Ti6Al4V matrix grain boundaries [9]. Figure 4 (a) shows the wear volume loss of Ti6A4V and Ti6Al4V/TiC particles with different vol%. It was seen from the figure 4(a) that an increase in the vol% of TiC led to the decrease in the wear volume or wear loss.



(a)



(b)

Figure 4: (a) Wear volume loss of Ti6A4V and Ti6Al4V/TiC reinforced specimens with contact loads of 10 N[9]; (b) Histogram chart of wear volume against the scanning velocity [18]

In an experiment conducted by Mahamood et al under a dry condition environment on a CETR tribotester using a Tungsten Carbide of 10 mm diameter ball and a load of 25 N with a sliding distance of 2000 m, the wear scar of the substrate were reported to show the ploughing grooves with some of the loose debris. A strong adhesion existed due to the frictional force between the two surfaces and the chemical properties of Ti6A4V. The combination of the adhesion and the rubbing action instigated the formation of debris and the high temperature occurrence within the surface. The size of the unmelted carbides as reported in Figure 3(c) deposited at scanning velocity of 0.065 m/s was smaller when compared to samples deposited at higher scanning velocity of 0.105 m/s. This was due to the fact that, smaller unmelted carbides were melted at lower scanning velocity and left with larger particles[18]. The histogram plot of wear volume against the scanning velocity of the substrate and the deposited Ti6Al4V/TiC alloy was showed in Figure 4(b). The substrate was reported to show the highest coefficient of friction and highest wear volume as compared to all other samples due to the chemical property of the Ti6Al4V that makes them to react with any contacting surfaces. The presence of TiC has really improved the wear resistance performance .The sample deposited at the scanning velocity of 0.065 m/s was revealed to give the best wear resistance performance. A low scanning speed was also reported not to improve the wear performance due to high dilution rate [18].

2.4. Microstructural characterization

The microstructural characterizations of the composites are presented in the section. Different authors have discussed the results of the microstructures based on the parameters and mode of composite formation.

Mahamood et al discussed the effect of scanning speed on the microstructures Ti-6Al-4V/TiC composite. The microstructure of the substrate (Ti6Al4V alloy) was first characterized. A bimodal structure of both α and β phases was observed with the β-phase (dark phase) distributed within the vicinity of α-phase (brighter phase). Globular grains were reported to form towards the substrate as the heat from the melt pool conveyed into the interface region [18].

Figure 5 (a) shows the microstructure of the composite deposited with a scanning velocity of 0.055 m/s.

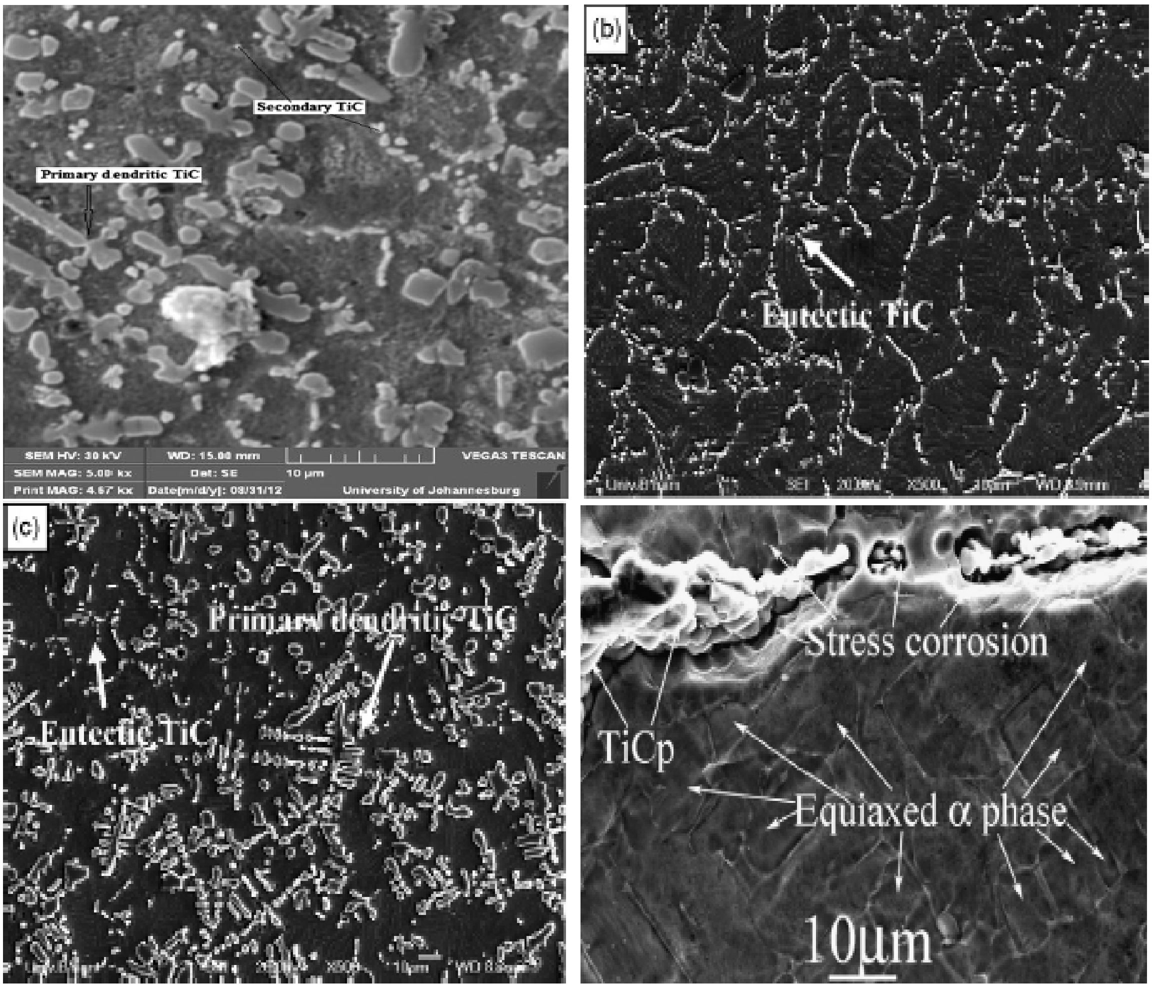


Figure 5: (a) SEM micrograph of sample deposited at scanning speed of 0.055 m/s showing primary dendritic and secondary carbide [18]; (b) Secondary electron micrograph of Ti6Al4V/TiC composite at a feed rate of 0.14 g/min. (c) Ti6Al4V/TiC composite at a feed rate of 0.44 g/min [9]; (d) SEM micrograph of Ti6Al4V/TiC composite with a network microstructure after serious etching [14]

The primary and secondary dendrites of TiC microstructures were observed. The secondary dendrites of TiC were reported to have emerged from the primary dendritic TiC which led to the reduction in the size of the primary dendritic phase. The scanning speed has a significant effect on the increased size of the secondary dendrites of TiC. The occurrence was attributed to the rate of solidification and the laser material interaction time at a high scanning speed [18] .

Figures 5 (b and c) show the scanning secondary electron micrographs of Ti6Al4V/TiC composites at the feed rates of 0.14 g/min and 0.44 g/min respectively.

Wang et al discussed the microstructures of laser-fabricated Ti6Al4V alloy- that it comprises of coarse α laths of diverse bearings and attached with segmental volume of β phase and also forming basket weave-like Widmanstatten. The segmental volume of TiC was observed to increase with eutectic carbide. Primary dendrites of TiC were also observed [9]. Unmelted carbides were also detected at high powder flow rate [9]. The increase in scanning speed has also played an important role in the size of the unmelted carbides. The laser-material interaction time has been reported to influence their formation [18].
The formation of equiaxed microstructure of titanium alloy was presented by Huang et al, that the solider TiC link can efficiently force the congestion of the Ti6Al4V alloy when cooling above the transus temperature. The behaviour was reported to form an isotropic tensile stress state within the entire Ti6Al4V composite and which later led to severe stress corrosion during etching. Figure 5 (d) showed an illustration of the stress corrosion attack. During cooling, the solider TiC link was also stated to effectively obstruct the new α phase formation and nucleation. The obstruction created by the TiC is beneficial to the formation of the equiaxed microstructure and decrease the phase transformation temperature. Diverse coefficients of thermal expansion of the titanium matrix and the TiC was also reported to strengthen the isotropic tensile stress [14].

Jun et al revealed in their work when TiB and TiC were synthesized with titanium alloy. The morphologies of TiB and TiC phases in the coating were reported to have uniform coarse primary cellular dendrites of α-Ti, eutectic transformation of coarse rod-shaped and a fine needle-like shaped surrounded with uniform and limited equiaxial particles of TiC. They revealed that the differences in the morphology of TiB and TiC could be attributed to changes in their crystal structures [16]. The modifications in the crystal structures caused the TiC to grow in an equiaxial or near-equiaxial shape when it is precipitated by the binary eutectic reaction [21].

3. CONCLUSION

After reviewing the literatures on what has been done so far on the reinforcement of Ti-6Al-4V and TiC, it was observed that in most of the literatures the mechanical properties of the alloy reinforced alloy samples have greatly improved compare to the parent sample Ti-6Al-4V. In other word the surface modification of the parent material has been greatly implemented and successively achieved in all the literatures reviewed so far.

Acknowledgments

I strongly acknowledge the authors of the different journals used for this reviewed article for their great research and experimental work and my diligent supervisor, a senior lecturer from Department of Mechanical Engineering Science, University of Johannesburg, Auckland Park Kingway Campus, Johannesburg.

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