SiC and Al surface cladding of Ti-6Al-4V for improved wear properties – The binary advantage

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ABSTRACT: Ti-6Al-4V enjoys high specific strength, toughness and excellent corrosion resistance, but suffers high friction coefficient, severe adhesive wear and sensitivity to fretting wear. Laser surface cladding is one of the surface modification techniques used for improving on these demerits. Using a 4.4Kw continuous wave Nd-YAG laser processor, the surface cladding of as received Ti-6Al-4V alloy was done with mixtures of SiC and Al powders in different ratios. The SiC powder can serve as reinforcing particles and helps improve surface wear properties in resulting surface metal matrix composite while aluminium improves on the wetting between the metal and the reinforcement SiC phase. The success of this, however, depends on the careful optimisation of the powder ratio, which dictates the resulting phases and microstructural evolutions. Study of the cladding with scanning electron microscope (energy dispersive spectroscopy), optical microscope and x-ray diffraction revealed formation of intermetallic phases such as AlSiTi2, Ti7Al5Si12, AlSi3Ti2, AlTi3, Al2Ti19, Ti2VAl, AlTi3, AlCTi2, T3SiC2 and Ti5Si3, which should enhance micro-hardness and tribological properties of the surface relative to the bulk as-received alloy. 90:10 weight percentage ratio of SiC and Al powder mixture gave the best microhardness with a value of 1169.95 Hv, compared to 323.67 Hv of the as-received, and mass loss under abrasive wear tests was only 40% of the as received. The morphology obtained for the abraded surfaces is also indicative of this improvement. In carefully optimised proportions and laser condition, the binary combination of Al and SiC powders suffice for well improved Ti-6Al-4V surface properties.

1. Introduction
Some properties of Ti-6Al-4V that make it an invaluable material in the aerospace industry are; high specific strength (strength to density ratio), toughness, and excellent corrosion resistance [1]. Ti-6Al-4V is a preferred titanium alloy because of its right balance of characteristics which includes strength, creep characteristics, fracture toughness, and the ability to retain its mechanical properties at elevated temperatures [2, 3]. The Ti-6Al-4V alloy would have enjoyed better patronage in more diverse applications if not for its poor tribological properties. Two main factors cause the poor tribology of Ti-6Al-4V: one, weak resistance to plastic shearing and poor work hardening; causing, the alloy to react poorly to adhesion, abrasion and delamination. Two, the oxides formed under high-temperature flashes under friction, has a low protective capacity, as this oxide is easily removed by spalling, and exposes a new surface to wear. The surface matrix also gets embrittled by dissolved oxygen from the atmosphere, which tends to reduce its mechanical and tribological properties [4]. Laser cladding is one of the means to alleviate these surface challenges of Ti-6Al-4V. Laser cladding utilises high power density available from a focused laser source to heat and melt the substrate’s surface while injecting alloying elements into the melt pool. The process often results in the formation of an alloyed zone confined to a shallow depth from the surface, it also results in the formation of a unique metallurgical bond with beneficial
microstructures and high concentration of critical elements, due to rapid cooling. A range of unique microstructures can be achieved by the processing method. These structures primarily depend on the laser processing parameters and powder/alloy compositions [5-7]. Silicon carbide displays exemplary configurations of physical and mechanical properties; it has a relatively low density of 3.21 g/cm³ at 25 °C making it attractive to the aerospace industries, excellent oxidation resistance and retention of strength at high temperatures with fracture stress of about 835 MPa at 1527 °C [8, 9]. Aluminium alleviates the challenge of poor interfacial bonding strength encountered in metal matrix composites (MMC), in this case between the Ti-6Al-4V matrix and the SiC reinforcement phase. This, however, requires careful optimisation of powder ratios and laser power conditions to ensure the evolution of microstructures favourable for improved properties. The focus of this work is exploring varying aluminium and silicon carbide powders ratios after first optimising the laser power and operation. The report here focuses on the powder ratio optimisation for good wetting of the laser melt pool during laser cladding. The coating depth, microstructural evolutions, microhardness and enhanced abrasive wear resistance were studied.

2. Experimental

2.1 Materials and Methods

Ti-6Al-4V is the substrate in this work and was sourced from Zhejiang Shenji Titanium Industry Co Ltd, in annealed conditions, with the dimensions of 70 mm x 70 mm x 5 mm; the nominal composition of the alloy is 6.01 wt% Al, 3.84 wt% V, 0.30 wt% Fe 0.15 wt% Si, 0.10 wt% C, 0.15 wt% O, 0.15 wt% N, Ti the balance. The Ti-6Al-4V substrate was sandblasted (to increase the intensity of the laser radiation at the surface) [10] and afterwards rinsed with acetone. Silicon carbide of different aluminium additions was used for laser cladding. The powders were sourced from TLS Technik GmBH. The particle size distribution (PSD) analysis indicates that the average powder particle size of the SiC powder 106µ was while Al was 75µ. Table 1 shows the powder compositions of the four powder mixes used in the investigation.

| Sample | Mix | Cladded surface | Powder Composition |
|--------|-----|----------------|--------------------|
| 1      | Mix1 (Single) | CS1 | 100 wt. % SiC |
| 2      | Mix2 (Binary) | CS2 | 90 wt. % SiC + 10 wt. % Al |
| 3      | Mix3 (Binary) | CS3 | 80 wt. % SiC + 20 wt. % Al |
| 4      | Mix4 (Binary) | CS4 | 70 wt. % SiC + 30 wt. %Al |

A 4.4 kW rofin Sinar continuous-wave Nd: YAG (neodymium-doped yttrium aluminium garnet) laser equipped with an off-axis nozzle for powder feeding and a fibre-optic beam delivery system, was used for laser surface cladding of the substrate. Optimal laser parameters were established before the laser alloying. The optimisation process involved several trial runs, in which several laser parameters which include power, scan speed, beam diameter, the powder feed rate was varied to determine the optimum parameter, that is the parameter that yielded the best coating. Determination of the best coating was done on the spot after each trial run, by examining the quality of the finish. Table 2 is the optimum laser processing parameters.

| Powder Composition | Power (Kw) | Scan Speed(m/sec) | Beam Diameter(mm) | Powder feed rate(g/pm) | Argon gas flow (L/min) | Track overlap percentage |
|--------------------|------------|------------------|-------------------|------------------------|------------------------|-------------------------|
| 100 wt. % SiC      | 1.2        | 0.8              | 4                 | 5                      | 2                      | 50                      |
| 90 wt. % SiC + 10 wt. % Al | 1.2 | 0.8 | 4 | 5 | 2 | 50 |
| 80 wt. % SiC + 20 wt. % Al | 1.2 | 0.8 | 4 | 5 | 2 | 50 |
| 70 wt. % SiC + 30 wt. % Al | 1.2 | 0.8 | 4 | 5 | 2 | 50 |
2.2 Characterisation of As Received and Cladded Surfaces

The as-received Ti-6Al-4V and cladded samples were cross-sectioned using a Struers Discotom-2 cutting machine which has a cut-off wheel; The samples were ground using SiC paper ranging from 200 to 1200 grit and then polished using diamond impregnated cloths ranging from 3 to 1 micron; Finally, the samples were cleaned, dried and etched with krolls reagent (6 ml HNO3 + 2 ml HF + 92 ml H2O) for microscopic observation and characterisations. Scanning electron microscope (SEM) equipped with energy-dispersive x-ray spectroscopy (EDS) was employed for the microstructural analysis, with phase constituents of the alloyed surface characterised using x-ray diffractometer (XRD). The scan was taken between 5° and 90° 2 thetas (2θ), and the phases present were identified using Deffrac Eva software with an in-built international centre for diffraction data (ICSD) database. The cladded zone, as shown in Figure 1, was subjected to microstructural analysis. Characterisation of the cladded zone was done in order to have a perfect view of the microstructural evolutions in the alloyed zone.

2.3 Microhardness and Tribological analysis

The specimen was tested for surface hardness using a micro Vickers hardness tester according to ASTM E384 standards: microhardness measurements along the depth direction for all the cladded samples, with a load of 1000 grams, as schematically illustrated in Figure 2. A depth direction indentation from the surface through the substrate was done. Average of 4 indentations were taken and reported as the average microhardness of the cladded surfaces.

Three bodies abrasive wear tests were carried out to determine the wear rate of the samples under severe abrasive conditions. Silica sand with a particle size range of about 0.3–0.65mm was used as the third body, at a load of 1500N at a constant speed of 100- rpm. A relatively high load (1500N) was used to ensure severe and proper abrasion of the cladded surface and substrate with the stainless-steel wheel. Figure 3 is a schematic illustration of the operation. The wear mechanisms of the best surface (in terms of coating depth, homogeneity and microhardness) was compared with that of the substrate at the same testing conditions.

The samples were weighed before and after abrading using a 1 mg precision electronic balance. The samples were abraded thrice, each time for five minutes, after which they were rinsed in acetone to ensure removal of all wear debris. Average wear rate per minute over the 15 minutes total abrasion time was calculated for the samples. Evaluation of the worn surface to determine the morphology of the wear track was done using the Scanning electron microscope.
3. Results and Discussions

3.1 Coating Thickness

Figure 4 depicts the average coating thickness of the laser cladded sample surfaces, which was about 712, 1047.81, 1087.35 and 909.42 microns under different conditions. The variations in the coating depths result from degrees of interactions in the melt pool, which also dictates the metallurgical bond between the coating and the substrate. The formation of phases in the coating layer depends on the wettability of the contact surface, nucleation and growth properties of each phase, chemical reactions between interacting phases and diffusion rates of the reacting species through the interlayer\[11\]. Wettability could be defined as the propensity of a fluid to spread on or stick to a solid surface amid other immiscible fluids. Wettability points to the interaction between the fluid and solid phases. The contact angle of fluid with the solid phase defines wettability. Laser scans develop a large thermal gradient between the centre and the edge of the melt pool at the surface, temperature gradient gives rise to a corresponding variation of the surface tension between the centre and the edge of the melt pool, consequently, thermocapillary forces for fluid flow are induced, known as Marangoni flow \[12\]. The Marangoni flow in combination with poor wetting conditions in the melt pool causes the restriction of the melt from spreading outwards on the underlying surface hence preventing proper interaction between the substrate and the pool \[13\]. The SiC powder has limited wettabillity with the Ti-6Al-4V melt, and this restricts depth of the coating \[14\].

The coating depth recorded in the binary powder coatings was much higher than that of the single powder cladding (CS1, 100 wt% SiC) which was 712 microns. The coating depth enhancement could be attributed to enhanced wetting of the SiC in the melt pool during the laser cladding process. The coating depth is beneficial to the underlying substrate as it provides cover and extends the lifetime of the substrates in service. Aluminium alleviates the challenge of interfacial bonding strength encountered in metal matrix composites (MMC), between the matrix and reinforcement phase, the addition of aluminium improves the poor wetting conditions between ceramic powders in the metal matrix. The addition of aluminium significantly improved the wetting of SiC. Aluminium wet SiC even at the vicinity of its melting point, the wettabillity the carbides are improved because of the formation of new phases \[15\]. Good wetting in the melt pool, enhanced the outward spreading of the melt to the underlying surface, thus expediated proper interaction between the substrate and the pool \[13\]. Proper interaction between the substrate and the pool led to the formation of new intermetallic phases, adequate surface bonding between the coating and the substrate and thicker coating. The evidence of the enhanced wetting of the melt pool is shown in the optical micrographs and XRD data of the single and binary powder cladded surfaces. However, a thicker coating may not immediately imply better wear behaviour and protection. The relevant characterizations for informed decisions are discussed following.

3.2 Phase Evolution

Figures 5 and 6 are the optical and electron micrographs of the laser cladded surfaces, respectively. The optical micrographs of the laser cladded surfaces in Figure 5 show the coatings samples are composed of several distinct phases. CS1 had only the dark irregular phase noticeable, while the binary powder coatings witnessed some other remarkable transformations in the coating matrix. These further matrix
transformations evidence the enhanced wetting of the binary powders in the melt pool. CS2 shows the residual SiC in a darker matrix relative to the other cladded surfaces. At higher aluminium, (CS3 and 4) the dark matrix phase became remarkably lighter with other distinct phase evolutions. CS4 had a needle-like matrix, and a threadlike matrix evolves in the alloy matrix (Figure 5d). With a distinct evolution of different phases at higher aluminium proportion, the coating properties would have changed remarkably. The SEM/EDS study gave further information on the composition of these phases. The SEM shows the presence of the residual SiC phase in a dark matrix. The irregular phases are uniformly distributed, and they can be seen to have good interfacial bonding with the Ti-6Al-4V matrix. A uniform cladding layer with no cracks was obtained for all powder mix ratios. From the EDS data (Figure 7, spectrum 1), the residual SiC phase consists of silicon and carbon, confirming that the phase is residual SiC. Dissolution of SiC and the substrate alloy gives rise to a melt pool where Si, Ti and C are the main components in different quantities based on the powder mix ratios. The resultant phase composition is heavily dependent on the prevailing thermodynamic of the elements [16]. Comparing Figure 6b, 6c and 6d, it was apparent that an increase in the percentage of aluminium powder in the matrix increased the darker matrix under the SEM. This indicates the presence of a phase with lower secondary electron intensity. In optical micrograph, this appears as a brighter matrix. The EDS of the CS4 shows elemental compositions of the needle-like matrix, which had close to 50 wt% aluminium (Figure 7, spectrum 3). It is expected that this huge quantity of aluminium will affect the service properties of this sample in some definite ways.

Figure 5. Optical bright fields micrographs of laser cladded Ti-6Al-4V with (a) 100 wt% SiC (b) 90 wt % SiC, 10 wt% Al (c) 80 wt % SiC, 20 wt% Al and (d) 70 wt % SiC, 30 wt% Al.

Figure 6. SEM backscattered electron micrographs of laser cladded Ti-6Al-4V with (a) 100 wt% SiC (b) 90 wt % SiC, 10 wt% Al (c) 80 wt % SiC, 20 wt% Al and (d) 70 wt % SiC, 30 wt% Al.
The formation of phases such as TiSi$_2$, Ti$_7$Al$_5$Si$_{12}$ and AlCTi$_2$, shows the laser energy and solution condition in the melt pool suffice to decompose the carbide and allow its elements to form separate phases in the cladding. These carbide, aluminide and silicide phases will enhance the surface properties diversely. Figure 7 is the XRD diffractograph of the as-received Ti-6Al-4V showing the various peaks of titanium atoms.

**Figure 7**: EDS spectrums of various spots in laser cladded Ti-6Al-4V with 70 wt% SiC + 30 wt% Al

| Spectrum | C     | Al   | Ti   | Si   | V    |
|----------|-------|------|------|------|------|
| 1        | 40.50 | 59.49|
| 2        | 4.29  | 5.69 | 85.77| 0.69 | 3.56 |
| 3        | 23.00 | 49.67| 17.42| 9.59 | 0.32 |

**Figure 8**: XRD spectral of as received Ti-6Al-4V
Figure 9. XRD spectral of cladded samples laser cladded Ti-6Al-4V using 100wt % SiC, 90 wt%SiC + 10 wt% Al, 80 wt% SiC + 20wt % Al and 70 wt% SiC + 30 wt% Al.

From the XRD of the surface layer, Ti$_5$Si$_4$, Ti$_3$V$_3$Si$_5$, Ti$_3$Si$_3$, AlSiTi$_2$, Ti$_7$Al$_5$Si$_{12}$, TiSi$_2$, AlSi$_3$Ti$_2$, Al$_6$Ti$_{19}$, Ti$_2$VAI, AlTi$_3$, AlCTi$_2$, Ti$_3$SiC$_2$, Ti$_5$Si$_4$ and Ti$_5$Si$_4$ were identified. Figure 8 shows the diffractograph obtained during the XRD study, indicating the angles at which the peaks of these phases were identified. The formation of these phases indicated that SiC and Al properly interacted and got alloyed with the titanium alloy substrate extensively. These intermetallic compounds were generated from chemical reactions in the molten pool involving large amounts of Ti element from the molten part of the matrix.
and Si, Al, V. From Table 3, it could be observed that the Ti_7Al_5Si_12 phase was consistent through the binary powder cladded surfaces, the Ti_7Al_5Si_12 phase has been noted for increasing the wettability of Al- ceramic composites [17]. This is further evidence of an enhanced wettability of the melt pool by the action of the binary powders of SiC and Al.

3.3 Microhardness and Abrasive Wear

Table 3 depicts the microhardness, and phases formed at the alloyed zone. The results indicate that CS2. The ternary Ti-Al-Si phase diagram can give insight about possible phases at this range of composition, but there are vanadium and other microelements in the as-received alloy (See Section 2.1). CS2 had the overall best microhardness behaviour, thus indicating the optimum aluminium content of 10% in the matrix. The increase in overall microhardness of the processed alloy could be attributed to the combined effects of the new intermetallic phases and formation of the Ti_5Si_3, Ti_5Si_4 and Ti_7Al_5Si_12 reinforced phases. The Ti_5Si_3, Ti_5Si_4 and Ti_7Al_5Si_12 reinforced phases have some outstanding advantages, such as high hardness, excellent wear resistance, high melting point, high thermal stability and excellent high-temperature oxidation resistance and enhanced mechanical properties [17, 18]. More so, laser cladding involves a high rate of heating and cooling which leads to massive grain refinement of the alloyed zone, this, in turn, enhances the surface properties of the surface, which microhardness is one of them.

Table 3. Average microhardness (Hv) under a load of 1000g and phases in the coatings at different powder compositions

| Sample | Powder composition | Microhardness (HV) | Phases present (XRD) |
|--------|--------------------|--------------------|----------------------|
| As received | -                   | 323.67             | Ti (alpha & beta)    |
| CS1    | 100 wt% SiC        | 910.25             | Ti_5Si_4, AlSi_3Ti_2, Ti_5V, Ti_5Si_3, Ti_5Si_4 |
| CS2    | 90 Wt% SiC + 10 Wt% Al | 1169.95           | AlSi_3Ti_2, Ti_7Al_5Si_12, Ti_5Si_2 |
| CS3    | 80 Wt% SiC + 20 Wt% Al | 732.30             | AlSi_3Ti_2, Ti_7Al_5Si_12, Al_5Ti_9, Ti_2VA, AlTi_3, AlCTi_2 |
| CS4    | 70 Wt% SiC + 30 Wt% Al | 428.85             | AlSi_3Ti_2, Ti_7Al_5Si_12, Ti_5SiC_2, Ti_5Si_4 |

Figure 10 illustrates the wear rate of the as-received and cladded surfaces under severe three bodies abrasive wear at the load of 1500N. The Ti_5Si_3, Ti_5Si_4 and Ti_7Al_5Si_12 reinforced phases present in the sample surfaces played a massive role in the wear resistance of the laser cladded surfaces. It was evident that the as-received had higher wear rates than CS1 and 2 for the time interval. However, CS4 had a higher wear rate than the as received. This inferiority of CS4 could be attributed to the quantity of aluminium present at the needle like matrix (Figure 7, spectral 3).

The wear tracks of the as-received as shown in Figure 10a and CS4 (Figure 10d) exhibits grooves and ridges in the sliding direction of the stainless-steel wheel, and the presence of agglomerated wear debris was observed in between the grooves and ridges. The agglomeration of the wear debris was caused by the generation of heat involved in the dry sliding, and frictional forces present between two rubbing surfaces. In the three-bodies abrasive tests, the samples were abraded by the action of a stainless-steel wheel and silica sand particles. Plastic deformation occurred on the as-received alloy as a result of the
cumulative effects of abrasion caused by the sand and fatigue induced by the rotating stainless-steel wheel. From Figure 10, it can be observed that the worn surface of CS1 and 2, exhibited fewer grooves, pits and accumulated wear debris when compared to the as-received alloy and CS4. It can be concluded that the wear mechanism was characterised by mild abrasive wear behaviour relative to the CS4 and the as received Ti-6Al-4v surface. CS1(100 wt% SiC) had the best abrasive behaviour, due to the abrasive nature of pure SiC used for the cladding experiment.

**Figure 10.** Average wear rates as-received Ti-6Al-4V and laser cladded Ti-6Al-4V using 100 wt% SiC, 90 wt% SiC + 10 wt% Al, and 70 wt% SiC + 30 wt% Al, after severe three bodies abrasive wear at a load of 1500N.

**Figure 11.** SEM secondary electrons micrograph of the worn surface morphology after severe 3 bodied abrasive wear at a load of 1500N of (a) as-received Ti-6Al-4V (b) laser cladded Ti-6Al-4V using 100 wt% SiC (c) laser cladded Ti-6Al-4V using 90 wt% SiC + 10 wt% Al. (d) laser cladded Ti-6Al-4V using 70 wt% SiC + 30 wt% Al

4. Conclusions
Successful laser cladding was done on Ti-6Al-4V alloy using single and binary powder compositions of SiC and Al; Several microstructural evolutions were observed as the powder compositions were varied. The coating thickness of all the binary cladded samples was higher than the single powder cladding using 100% SiC powder. This was attributed to the enhanced wetting of the binary powders. Wetting of SiC and Al resulted in the formation of various intermetallic as indicated by the XRD micrographs which include AlSiTi2, Ti7Al5Si12, TiSi2, AlSiTi2, Al5Ti19, Ti2Al, AlTi1, AlICTi2, T13SiC2 and Ti5Si4. There was an enhanced microhardness, as all the cladded samples had higher average microhardness (1169.95 – 428.85 Hv) than the as-received (323.67 Hv). The microhardness behaviour of CS2 (90 wt% SiC + 10% Al) was the best, thus indicating that the optimum weight percentage of aluminium in the matrix should be about 10%. CS1(100wt % SiC) recorded better abrasive wear rate than the other cladded surfaces because of the abrasive nature of pure SiC used in the cladding.

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References

[1] Zhang Z X, Qu S J, Feng A H and Shen J 2017 Achieving grain refinement and enhanced mechanical properties in Ti–6Al–4V alloy produced by multidirectional isothermal forging Mater Sci Eng, A 692 127-38

[2] Tchein G J, Jacquin D, Aldanondo E, Coupard D, Gutierrez-Orrantia E, Girot Mata F and Lacoste E 2019 Analytical modeling of hot behavior of Ti-6Al-4V alloy at large strain Mater Des 161 114-23

[3] Inagaki I, Shirai Y, Takechi T and Ariyasu N 2014 Application and Features of Titanium for the Aerospace Industry. (http://www.nssmc.com: Nippon Steel & Sumitomo Metal Technical Report)

[4] Molinari A, Straffelini G, Tesi B and Bacci T 1997 Dry sliding wear mechanisms of the Ti6Al4V alloy Wear 208 105-12

[5] Popoola A P I, Fatoba O S, Nkosi H W and Aigbodion V S 2016 Surface hardening of Aluminum by Laser alloying with Molybdenum and Zirconium powder Int. J. Electrochem. Sci 11 13

[6] Nkosi H W, Popoola A P I and Abdulwahhab M 2012 Laser surface alloying of Al with Mo for hardness improvement

[7] Vora H D, Rajamure R S, Soundarapandian S, Srinivasan S G and Dahotre N B 2013 Dilution of molybdenum on aluminum during laser surface alloying J Alloys Compd 570 133-43

[8] Hayun S, Paris V, Mitrani R, Kalabukhov S, Dariel M P, Zaretsky E and Frage N 2012 Microstructure and mechanical properties of silicon carbide processed by Spark Plasma Sintering (SPS) Ceram Int 38 6335-40

[9] Touloukain Y S 1967 Thermophysical properties of high temperature solid materials vol 5 (New York: MacMillan CO)

[10] Adebiyi D I and Popoola A P I 2015 Mitigation of abrasive wear damage of Ti–6Al–4V by laser surface alloying Materials & Design 74 67-75

[11] Al-Sayed Ali S R, Hussein A H A, Nofal A A M S, Hasseb Elnaby S E I, Elgazzar H A and Sabour H A 2017 Laser Powder Cladding of Ti-6Al-4V α/β Alloy Materials (Basel, Switzerland) 10 1178

[12] Niu H J and Chang I T H 1999 Selective laser sintering of gas and water atomized high speed steel powders Scripta Mater 41 6

[13] AlMangour B, Grzesiak D and Yang J-M 2017 In-situ formation of novel TiC-particle-reinforced 316L stainless steel bulk-form composites by selective laser melting J Alloys Compd 706 409-18

[14] Man H C, Zhang S, Cheng F T and Yue T M 2002 In situ synthesis of TiC reinforced surface MMC on Al6061 by laser surface alloying Scripta Mater 46 229-34

[15] Laurent V, Chatain D and Eustathopoulos N 1987 Wettability of SiC by aluminium and Al-Si alloys J. Mater. Sci. 22 244-50

[16] Pleshakov E, Senyavs'kyi Y and Filip R 2002 Laser Surface Modification of Ti-6Al-4V Alloy with Silicon Carbide Mater Sci 38 646-52

[17] Juan L, Kehong W and Deku Z 2016 The Effect of Ti on Microstructural Characteristics and Reaction Mechanism in Bonding of Al-Ceramic Composite J Mater Eng Perform 25 3638-45

[18] Dai J, Zhang F, Wang A, Yu H and Chen C 2017 Microstructure and properties of Ti-Al coating and Ti-Al-Si system coatings on Ti-6Al-4V fabricated by laser surface alloying Surf Coat Technol 309 805-13