

Deposition of Ti/TiC Composite Coatings on Implant Structures using Laser Engineered Net Shaping

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Abstract

A new method of depositing hard and wear resistant composite coatings on metal-on-metal bearing surfaces of titanium implant structures is proposed and demonstrated. The method consists of depositing a Ti/TiC composite coating (~ 2.5 mm thick) on titanium implant bearing surfaces using Laser Engineered Net Shaping (LENS[®]). Defect-free composite coatings were successfully produced at various amounts of the reinforcing TiC phase with excellent interfacial characteristics using a mixture of commercially pure Ti and TiC powders. The coatings consisted of a mixture of coarser unmelted/partially melted (UMC) TiC particles and finer, discreet resolidified (RSC) TiC particles uniformly distributed in the titanium matrix. The amounts of UMC and RSC were found to increase with increasing TiC content of the original powder mixture. The coatings exhibited a high level of hardness, which increased with increasing TiC content of the original powder mixture. Fractographic studies indicated that the coatings, even at 60 vol.% TiC, do not fail in a brittle manner. Various aspects of LENS[®] deposition of Ti/TiC composite coatings are addressed and a preliminary understanding of structure-property-fracture correlations is presented. The current work shows that the proposed approach to deposit composite coatings using laser-based metal deposition processes is highly-effective, which can be readily utilized on a commercial basis for manufacture of high-performance implants.

Keywords: LENS[®]; Additive manufacturing; Composite coatings; Titanium carbide; Biomedical implant.

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* LENS[®] is the registered trademark and service mark of Sandia National Laboratories and Sandia Corporation.

1. Introduction

Materials used for biomedical implant devices must satisfy a variety of property demands, which are often mutually exclusive. Further, different parts of a device demand different material properties. These factors often make it difficult to manufacture a medical device using a single material. Many implant devices, such as knee replacements, involve a relative motion between constituent parts while in service. In such situations, polyethylene-on-metal bearing surfaces are currently being widely used due to the forgiving nature of the combination to the individual biomechanical nuances of joint recipients. Studies, however, show that, although polyethylene is biologically inert in the body as a whole, microscopic particles of polyethylene resulting from wear can possibly be toxic if encountered in large amounts and lead to osteolysis [1-3]. This has led to a growing interest in metal-on-metal bearing surfaces for implants, especially in applications involving a large contact area [4-5].

The metal-on-metal approach, however, requires the bearing surfaces to be extremely hard and wear resistant. Fabrication of an entire implant device from materials hard enough to satisfy these requirements is not plausible, as such hard materials would be too brittle to use. A more plausible approach would be to use a suitable hard surface coating on the bearing surfaces of the implant. This approach allows one to manufacture an implant device from well-established biocompatible materials with desired bulk characteristics, while the surface property requirements are met by using a biocompatible hard surface coating.

While the surface coating approach is certainly advantageous, it presents a number of challenges related to coating materials and coating methods. Some of the issues related to coating materials are: i) the coating material should be biocompatible, ii) the coating should not be brittle or prone to spalling, iii) the coating should be adequately hard and wear resistant, and iv) the coating material should be metallurgically compatible with the substrate material. While most of the candidate coating materials, such as carbides, borides and nitrides, easily meet the hardness and wear resistance requirements, all of them are inherently brittle and are often not metallurgically compatible with metallic implant substrate materials. Further, it is difficult to apply robust, residual stress free, single-phase non-metallic coatings due to their inherent brittleness and propensity to spalling when deposited in thin layers. For example, application of single-phase TiC coating on a Ti alloy substrate using a laser-based metal deposition process was shown to result in gross cracking [6]. These considerations led us to consider using a composite coating constituting a metallic matrix material and a hard non-metallic material, in the form of uniformly dispersed particles in the matrix. In this way, one can produce a coating with all the desired characteristics — the softer metallic matrix material provides toughness and metallurgical compatibility/bonding with the substrate, whereas the hard non-metallic reinforcing material ensures adequate overall coating hardness and wear resistance.

Another important issue is the method of coating application. Some of the challenges in this regard are: i) the coating method should be capable of producing sound, fully-dense composite coatings, ii) the coating method should be capable of achieving metallurgical bonding between the coating and the substrate material in order to ensure adequate bond strength, iii) the coating method should use minimal heat input in order not to cause excessive microstructural damage to the substrate material, iv) the coating method should allow precise control over the coating application area to facilitate coating application just where needed on the implant device, and v) the coating method should have a material deposition rate capable of achieving adequate coating thickness to resist spalling within a reasonable amount of time. Further, it may be desirable, depending on the specific application requirements, to produce a coating with a spatial

variation in the amount or type of second phase particles to facilitate application of functionally graded coatings for achieving superior coating performance. Gradual increase in second phase amount provides a smooth microstructural and/or chemistry transition, allowing coatings to be deposited without cracking problems. Most conventional coating processes, such as thermal spray processes, diffusion coating processes, arc welding-based cladding processes, vapor phase processes, and others, are not quite suitable in the current context, as each of them fail to satisfy one or more of the above requirements.

Laser-based metal deposition processes satisfy all of the above requirements and are thus quite promising for producing composite coatings on implant surfaces. In the current work, one of the commercially available laser-based metal deposition processes, Laser Engineered Net Shaping[®] (LENS), has been used. LENS[®] is a novel additive manufacturing process developed by Sandia National Laboratories for fabrication of fully-dense three-dimensional (3D) metallic objects. A schematic of the LENS[®] process is shown in Fig.1. Initially, a three-dimensional CAD model of the component to be built is generated and a computer program slices the model into a number of horizontal cross-sections or layers. These cross-sections are systematically created from bottom to top producing a three-dimensional object fully automatically. The deposition process begins with directing a focused Nd-YAG laser beam onto a substrate placed on the build platform capable of computer-controlled motion. The laser generates a small molten pool (typically 0.25-1 mm in diameter and 0.1-0.5 mm in depth) on the substrate. Powdered material at a selected rate is injected directly into the melt pool using a powder feeder. The molten pool solidifies rapidly as the laser beam moves away, forming a thin track of solidified metal welded to the material below along the line of laser scanning. A layer is generated by a number of consecutive overlapping tracks. After each layer is formed, the laser head, along with the powder delivery nozzle, moves upward by one layer thickness and the subsequent layer is generated. This process is repeated until the part is complete. The deposition process occurs inside an enclosed chamber filled with argon to prevent oxidation of the liquid metal. Although the process was originally developed for fabricating free-standing 3D parts, the process lends itself to layer-by-layer deposition of coatings of desired thickness.

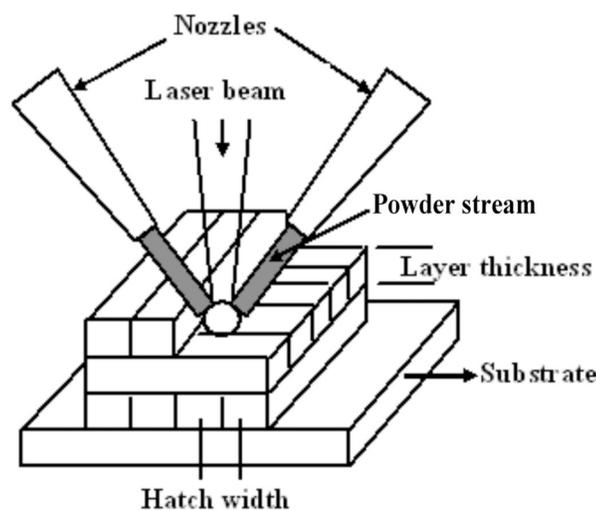


Fig.1. Schematic of the LENS[®] process.

The LENS[®] process has successfully been applied to fabrication of engineering components in materials like stainless steels, tool steels, titanium alloys, and superalloys [7-11]. Attempts have also been made to produce composite materials and functionally graded materials. For example, Banerjee et al. [12] produced a gradual transition in LENS[®] deposit composition and microstructure from binary Ti–8Al to Ti–8Al–20V within a length of 25 mm using elemental powders. Liu and DuPont [6] produced functionally graded Ti/TiC composite deposits using the LENS[®] process, employing separate powder feeders for introducing Ti and TiC powers in desired quantities. The investigators also fabricated TiC/TiAl composites, using preheated titanium substrates to prevent solid-state cracking in the deposit due to thermal stresses [13]. Similarly, Banerjee et al. [14] produced Ti-6Al-4V/TiB composite parts employing a blend of pure pre-alloyed Ti-6Al-4V and elemental B powders. In contrast, very few attempts have been made to utilize the process for the purpose of depositing a coating. Kumar and Stucker [15] have successfully deposited CoCrMo coating on a porous Ta substrate using the LENS[®] process employing Zr as an interlayer. While work by Liu and DuPont [6,13], and Banerjee et al. [14] are closely relevant in the current context, no reports are available on the use of the LENS[®] process for deposition of wear resistant Ti/TiC composite coatings on implant structures.

The current work explores the possibility of depositing Ti/TiC composite coatings on titanium implant surfaces using the LENS[®] process. Studies were directed to examine the effect of TiC volume fraction on coating formation, microstructure, and hardness, and to develop a preliminary understanding of structure-property-fracture correlations.

2. Experimental Work

Ti/TiC composite coatings 15x15x2.5 mm were produced using an Optomec 750 LENS[®] machine equipped with a 500 W Nd-YAG laser. The oxygen level in the deposition chamber was kept below 5 ppm during processing to avoid oxygen and nitrogen contamination in the deposit. The coating material consisted of a mixture of commercially pure (CP) Ti and TiC powders (–100/+325 mesh size (45-150 μm)). Prior to deposition experiments, Ti and TiC powders in selected quantities on a volume basis were thoroughly mixed in a blender and the mixture was fed into a powder feeder.

Table 1. LENS[®] parameters used for depositing Ti/TiC coatings.

Parameter	Level
Laser power (W)	165
Laser traverse speed (mm/s)	17
Powder feed rate (g/minute)	4
Layer thickness (mm)	0.12
Hatch spacing (mm)	0.25
Scan orientation (°)	0, 90, 0

Initially, powder mixtures were prepared containing 20% and 40% TiC by volume. Coatings produced using these powder mixtures will be referred to as Ti/20TiC and Ti/40TiC. For these experiments, a (CP) Ti wrought-processed sheet of 1 mm thickness was used as the substrate (substrate dimensions: 30 x 30 mm). The parameters employed for coating deposition are listed in Table 1. These parameters were found to result in sound coatings and were arrived at after preliminary deposition experiments involving the use of laser power, traverse speed,

powder feed rate, layer thickness, and hatch spacing at various levels. Scan orientation was changed (0° , 90° , 0°) for every layer in order to minimize residual stress build up.

After examining the microstructures of the Ti-20TiC and Ti/40TiC coatings, further coating experiments were performed with increased TiC content (60 vol.%) in the powder mixture. The coating produced with this powder mixture will be referred to as Ti/60TiC. For these experiments, a CP Ti wrought-processed plate 3 mm thick was utilized as the substrate (substrate dimensions: 100 x 50 mm). The process parameters utilized for these experiments are the same as those reported in Table 1.

Sections cut from LENS[®] deposits were prepared for microstructural examination following standard metallographic practices. Polished specimens were etched with Kroll's reagent (95 ml H₂O, 3 ml HNO₃, and 2 ml HF). Microstructural studies were performed using an Axiovert 100A inverted light microscope and a Hitachi S 4000 Scanning Electron Microscope (SEM) equipped with a field emission gun. In order to assess the fracture behaviour of coatings, coatings were fractured under impact loading and the fracture surfaces were examined under SEM. Hardness tests were performed on transverse sections of the coatings using a Vickers microhardness tester at a load of 300g. At least five tests were performed on each specimen and the average values were reported.

3. Results and Discussion

3.1 Coating Microstructures

The SEM microstructures of the Ti/TiC coatings (transverse section) produced using 20, 40, and 60 vol.% TiC powder mixtures are shown in Fig.2. All the coatings were found to be free from gross cracking, porosity and other defects. Individual layers/tracks in the coatings, characteristic of LENS[®] deposited materials, are apparent in these microstructures. The coating/substrate interface in all cases was observed to be free from defects, as can be seen in Fig.2d. Observations thus show that the LENS[®] process can produce sound Ti/TiC coatings over a wide range of TiC contents. In fact, successful LENS[®] deposition of a functionally graded Ti/TiC coating on a Ti-6Al-4V substrate, where the TiC content was increased from 0 to 95 vol.% (in the powder mixture), was reported by Liu and DuPont [6]. In the present study, coatings with higher than 60 vol.% TiC were not attempted for two reasons: i) use of large amounts of TiC can result in the formation of continuous carbide networks (as observed by Liu and DuPont [6]), which render the coatings brittle, and ii) deposition of coatings with a very high TiC content directly onto a Ti substrate can result in cracking at the substrate/coating interface (the situation is different when depositing a functionally graded coating, where the TiC content is gradually increased). In this context, Liu and DuPont [6] reported cracking problems in Ti/TiC composite coatings with 80 vol.% TiC, when the coating was directly deposited onto a Ti-6Al-4V substrate.

The microstructures shown in Fig.2 reveal the presence of quite a few irregularly-shaped, uniformly-distributed unmelted TiC particles (hereafter referred to as UMC), whose size ranged from 30 to 90 μm , in all the coatings. The amount of UMC can be seen to increase with increasing TiC content in the powder mixture, while the particle size appeared to be the same in all cases. Liu and DuPont [6] also reported similar observations. Quantitative image analysis on coating microstructures showed that the volume fraction of UMC in the three coatings was approximately 50% of the TiC content used in respective powder mixtures (Ti/20TiC, Ti/40TiC, and Ti/60TiC coatings contained 10.2, 19.5, and 28.6 vol.% of UMC, respectively). These

particles result from incomplete melting of the TiC powder particles originally introduced into the melt pool, whose size ranged from 45 to 150 μm .

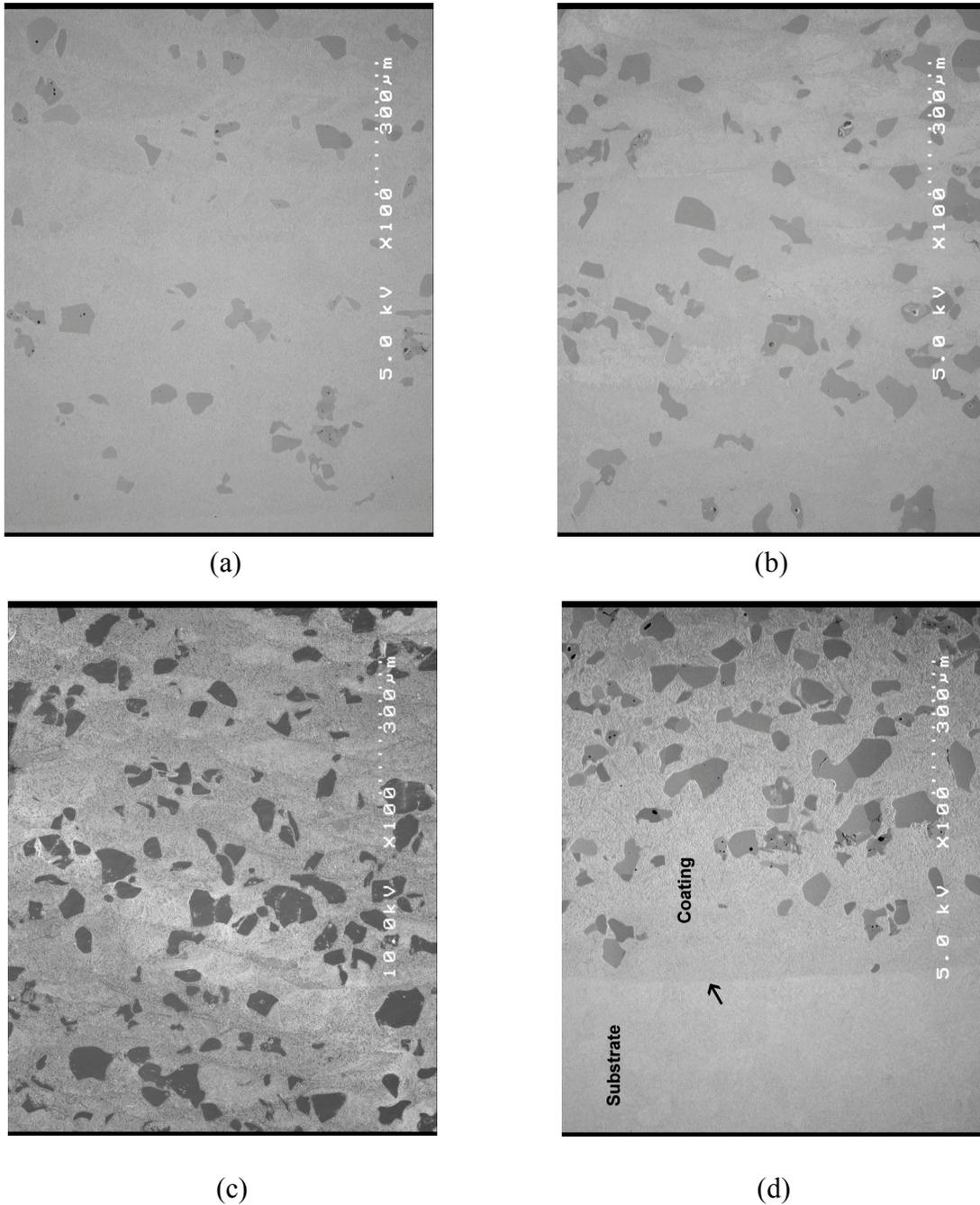


Fig.2. SEM microstructures of Ti/TiC composite coatings: (a) Ti/20TiC, (b) Ti/40TiC, (c) Ti/60TiC, (d) Ti/60TiC (coating/substrate interface shown by arrow).

A comparison of the amounts and size of TiC originally introduced in the powder mixtures with the volume fractions and size of UMC in the coating microstructures shows that TiC particles undergo considerable melting/dissolution during LENS[®] processing. It may be noted that the melting point of TiC (3160°C) is significantly higher than that of Ti (1668°C). In

spite of this, partial melting of TiC can occur during LENS[®] processing because of the higher laser absorption coefficient and lower thermal conductivity of TiC in relation to Ti [6]. Further, TiC particles can also experience some amount of dissolution in liquid titanium. The extent of TiC melting/dissolution is basically governed by the magnitude of incident laser energy and laser/TiC as well as liquid metal/TiC interaction times. Since all the three coatings were deposited using the same process parameters, it is only natural that the volume fraction of UMC increases with increased TiC content in the initial powder mixture.

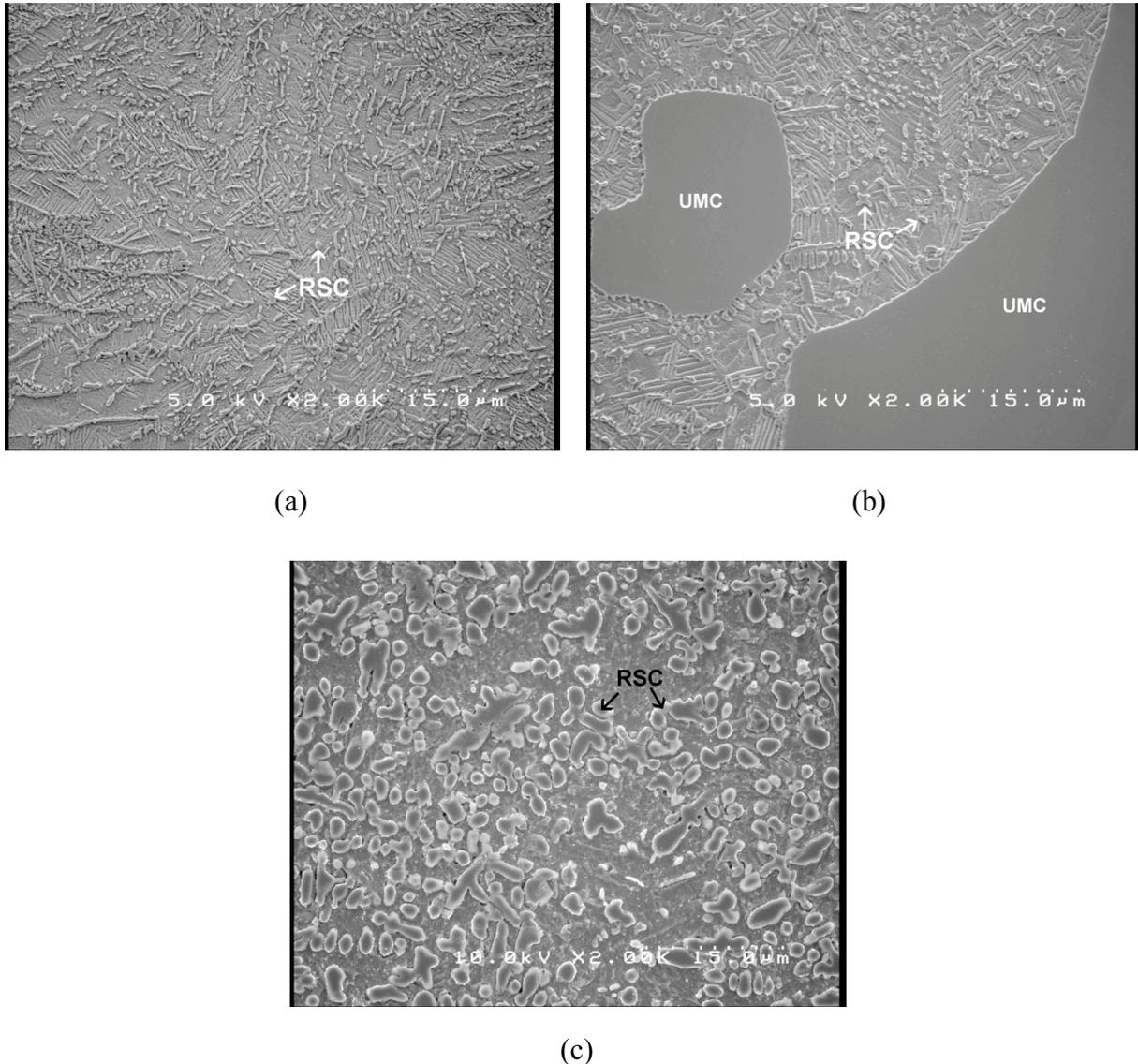


Fig.3. High magnification SEM microstructures of Ti/TiC composite coatings: (a) Ti/20TiC, (b) Ti/40TiC, and (c) Ti/60TiC. The plate-like features seen in (a) and (b) are coarse α -Ti plates.

Examination of coating microstructures at higher magnification revealed numerous finer TiC particles (about 1-4 μm) in all the coatings (Fig.3). These particles were confirmed to be non-stoichiometric TiC ($\text{TiC}_{0.65}$) by Liu and DuPont [6] based on X-ray diffraction studies. These finer carbide particles were found to be generally discrete and uniformly distributed in the

coating microstructure. A closer examination reveals that the non-stoichiometric TiC phase occurs in two different morphologies: i) slightly larger, dendritic-type TiC particles, and ii) very fine equiaxed TiC particles. The size and amount of dendritic type carbide particles appeared to increase with increase in TiC content in the powder mixture (Fig.3). The matrix in all cases consisted of martensitic α -Ti in a widmanstatten pattern. However, α -Ti plates appeared to be significantly coarser in Ti-20TiC and Ti-40TiC coatings compared to Ti-60TiC (Fig.3).

Development of microstructure in Ti/TiC composite coatings can be understood in the following manner. As noted earlier, the TiC particles present in the powder mixture undergo considerable melting/dissolution during LENS[®] processing. This results in carbon enrichment, consistent with the extent of dissolution, in the liquid metal. Solidification of this carbon-rich Ti melt takes the following sequence: $L \rightarrow L + \text{primary TiC} \rightarrow \beta\text{-Ti} + \text{TiC}$ eutectic [6,13]. Solidification starts with formation of primary TiC particles. According to the Ti-C phase diagram, C concentrations from approximately 0.5 to 16 wt.% C will form primary TiC during solidification [16]. Primary TiC appears as dendritic particles in the microstructure. As this happens, the carbon level in the remaining liquid comes down and eventually primary TiC formation would stop. When the eutectic temperature is reached ($\sim 1648^\circ\text{C}$), the $L \rightarrow \beta\text{-Ti} + \text{TiC}$ reaction takes place terminating the solidification process. The eutectic TiC would be finer and equiaxed compared to primary dendritic TiC. Thus at the end of solidification, the microstructure contains UMC particles, primary dendritic TiC particles, eutectic TiC, and β -Ti. Thus both primary dendritic TiC and eutectic equiaxed TiC form during solidification from a C rich Ti melt. These TiC particles will be referred to as resolidified carbide (RSC) particles. During cooling after solidification very little change in carbide microstructure occurs [6]. However, when the β -transus temperature ($\sim 900^\circ\text{C}$) is reached, β -Ti transforms to α -Ti. This transformation can occur either diffusively or martensitically or a combination of the two, depending on the cooling rates [17]. Because of the rapid cooling rates in the LENS[®] process (in the range of 10^4 to 10^5 $^\circ\text{C/s}$ during solidification [18], but likely lower during the solid-state transformation discussed here) this transformation is expected to occur almost entirely by martensitic transformation. Thus, the coating microstructure at room temperature consists of UMC and RSC in a matrix of widmanstatten martensitic α -Ti.

The observed differences in the microstructures of the three coatings can be explained as follows. The size and amount of primary dendritic TiC particles was observed to increase with increasing TiC content in the powder mixture (Fig.3). This should be a result of increased C content in the Ti melt. The estimated UMC volume fractions in the coatings indicate that approximately 50% of the TiC introduced in the powder mixtures melts/dissolves during LENS[®] processing in all cases. Consequently, C content in the liquid metal would increase with increasing TiC content in the initial powder mixture. An increase in C content in the liquid metal would mean more C availability for primary TiC formation. This results in more and larger primary TiC particles in the microstructure, as observed in the Ti/60TiC coating (Fig.3c). Further, higher carbon contents in liquid metal result in higher constitutional super cooling levels, which favor formation of primary Ti particles with a strong, pronounced dendritic shape [6,13]. This explains why primary TiC particles are more dendritic in appearance in Ti/60TiC coating than those in the other two coatings. It should be noted that the amount of eutectic TiC remains more or less the same in all cases, as primary TiC formation continues as long as the C content in the liquid is more than 0.5 wt. %, leaving the same amount of C in the remaining liquid before the eutectic reaction takes place.

The observed variations in matrix microstructure among the three coatings can be explained considering the differences in substrate dimensions. Ti/20TiC and Ti/40TiC coatings were deposited on a 1 mm thick Ti sheet (30 x 30 mm coupons), while the Ti/60TiC coating was deposited on a 3 mm thick Ti plate (100 x 50 mm coupons). Because of the larger substrate thickness and size (i.e., greater volume of heat sink), cooling rates would be higher in Ti/60TiC coating compared to the other two coatings. Substrate dimensions also determine the amount of heat built up during coating deposition. Because of the smaller substrate dimensions, there can be more heat built up in the Ti/20TiC and Ti/40TiC coatings than in the Ti/60TiC coating, although all the coatings were deposited using the same heat input. Consequently, these coatings experience significantly lower cooling rates, which affect β -Ti to α -Ti transformation. While β -Ti to α -Ti transformation can still be predominantly martensitic, the reduced cooling rates in these cases can result in some amount of diffusional transformation, leading to the formation of coarser, parallel plates of diffusional α .

Another factor that influences the matrix microstructure is multiple thermal cycling. LENS deposited materials experience a complex thermal history in a manner very similar to multi-pass weld deposits. The heat energy introduced during depositing a layer can reheat previously deposited material into various phase fields. The thermal cycle experienced can be different at each point in the reheated material depending on its distance from the heat source. The multiple thermal cycles thus can result in coarsening of α -Ti plates in the matrix microstructure. These effects are expected to be more pronounced in Ti/20TiC and Ti/40TiC coatings due to a larger amount of heat built up expected in these cases.

3.2 Coating Hardness

The results of microhardness tests on coatings and a CP Ti substrate are given in Table 2. Hardness measurements in the coatings were performed in matrix regions (i.e., away from UMC particles in the coating microstructures). Therefore, the reported coating hardness values represent the hardness of the Ti matrix with finer RSC particles. The bulk hardness levels of the coatings are expected to be higher than the reported values, as UMC particles also contribute to coating hardness during bulk hardness testing.

Table 2. Results of Vickers microhardness tests (average of 5 measurements).

Coating	Hardness (VHN)
Ti/20TiC	410
Ti/40TiC	760
Ti/60TiC	1190
Ti substrate	195

As can be seen in Table 2, all the coatings exhibited significantly higher hardness values when compared to the CP Ti substrate due to the presence of carbide particles. Coating hardness can be seen to increase with increasing TiC content in the original powder mixture. This correlates well with microstructural observations. As noted previously, the amount and size of RSC particles increased from Ti/20TiC to Ti/40TiC to Ti/60TiC. Consequently, Ti/40TiC and Ti/60TiC coatings exhibited relatively higher hardness levels when compared to Ti/20TiC coating. The results thus show that the hardness of titanium implant surfaces can be substantially increased by LENS[®] depositing a Ti/TiC composite coating. It may be noted that even higher

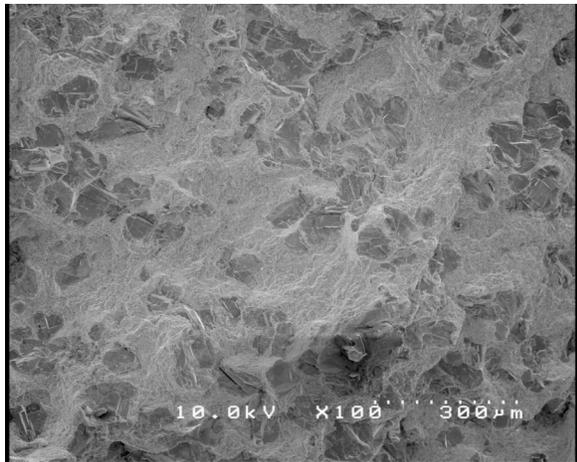
hardness levels are achievable in the coatings by simply increasing the TiC content in the coatings. However, there may be attendant problems as discussed in Section 3.1.

3.3 Fracture Behaviour of Ti/TiC Composite Coatings

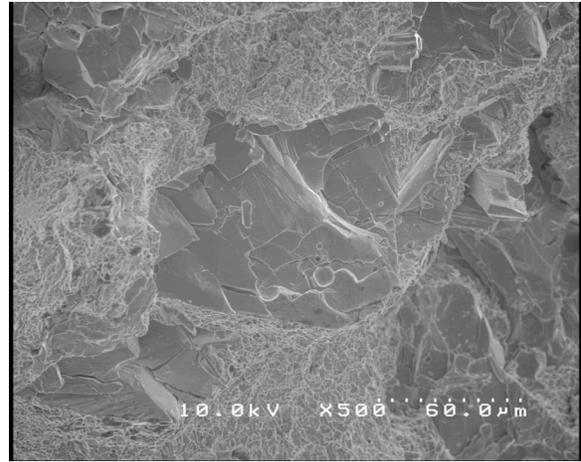
Ti/TiC composite coatings were fractured by applying an impact load to assess the fracture behaviour of the coatings. The SEM fractographs of a Ti/60TiC coating are shown in Fig. 4. All the coatings showed fractured UMC particles on the fracture surfaces (Fig.4a). It may be noted that there were no completely removed UMC particles on the fracture surface, which indicates that the UMC/matrix interfaces are strong (Fig.4a and Fig.4b). Examination of fracture surfaces, however, shows that UMC particles are fractured in a brittle manner during the fracture process (Fig.4c). Brittle fracture of UMC particles is no surprise considering the inherent brittleness of TiC. Importantly, the matrix regions (regions surrounding UMC particles, in Fig.4b and Fig.4c) exhibited ductile fracture features with well-defined dimples, as can be seen in Fig.4d. Some particles, presumably RSC particles, were seen inside the dimples, which suggest these particles served as void nucleation sites (Fig.4d). Nucleation of voids at hard second phase particles is quite common. Studies thus confirm that LENS[®] deposited Ti/TiC composite coatings do not fail in a brittle manner, even at relatively high levels of TiC content.

The presence of coarse UMC particles in the coating microstructure appears undesirable from many angles. First, UMC particles fracture in a brittle manner, leading to an overall reduction in coating toughness. Coatings can be made more ductile by eliminating the UMC particles. Second, UMC particles offer resistance to matrix shrinkage during solidification, which may result in generation of undesirable tensile residual stresses at the UMC/matrix interfaces. Third, UMC particles present favorable sites for formation of defects in the coating. Fourth, UMC particles may be removed early in the wear process, which may lead to significant third body wear. Finally, even without any contribution from UMC particles, reasonably high hardness levels are achievable in Ti/TiC coatings. Further studies involving metal-on-metal wear tests on Ti/TiC coatings are necessary to assess their wear performance and to see if the UMC particles are really undesirable.

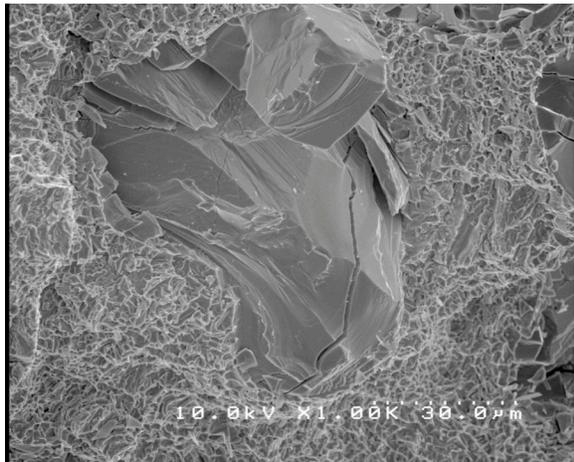
As demonstrated by Liu and DuPont [6], use of higher heat inputs facilitate more complete melting/dissolution of TiC particles in the powder mixture and, therefore, help eliminate or minimize UMC particles in the coating microstructure. However, use of higher heat inputs alone may not completely eliminate UMC particles, especially in coatings with a high level of TiC. Also, use of higher heat inputs can have other undesirable effects, such as formation of coarse microstructures and/or generation of excessive residual stresses, which may lead to cracking/delamination of the coating and affect coating properties. Another factor that assumes importance in this context is TiC particle size. Use of relatively finer TiC particles in the powder mixture can help eliminate or minimize UMC particles. Finer TiC particle sizes facilitate greater absorption of incident laser energy leading to greater melting of the particles. Finer particles also dissolve to a greater extent in the molten pool. Therefore, it should be possible to produce a Ti/TiC composite coating without a large number of coarse UMC particles by appropriately controlling the input TiC particle size without unduly increasing the heat input. However, care must be exercised to avoid use of very fine powders, as very fine powder sizes present difficulties with uniform powder feeding in the LENS[®] system.



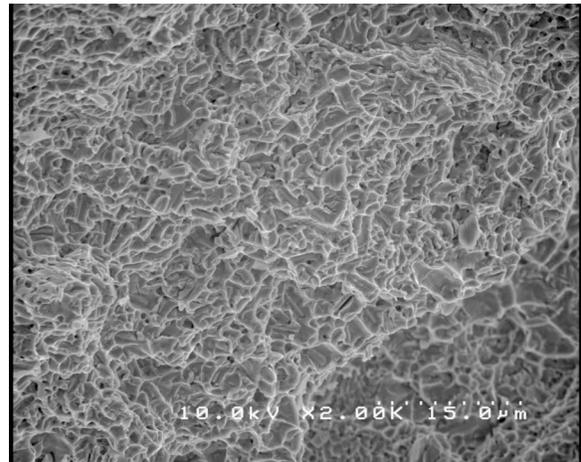
(a)



(b)



(c)



(d)

Fig.4. SEM fractographs of Ti/60TiC coating: (a) Fracture surface at a low magnification showing fractured UMC particles, (b) Fracture surface at a higher magnification showing brittle fractured UMC particles (note ductile fracture features in the matrix region), (c) Brittle fractured UMC particle at a higher magnification, and (d) Dimpled rupture features at a higher magnification in the matrix region.

4. Conclusions

- Metallurgically sound Ti/TiC composites can be deposited on titanium implant surfaces using Laser Engineered Net Shaping process. Coatings can be deposited over a wide range of TiC contents.
- Ti/TiC coatings show uniformly distributed partially melted TiC particles (UMC) and fine resolidified (RSC) TiC particles. The amounts of UMC and RSC increase with increasing TiC content in the powder mixture.
- Coating hardness increases with increasing TiC content in the powder mixture due to increased carbide precipitation.

- Fracture in Ti/TiC composite coatings occurs in a ductile manner. UMC particles fracture in a brittle manner, making their presence undesirable in the coating microstructures. UMC particles can be eliminated or minimized by controlling the input TiC particle size and by using higher heat inputs.

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