Chapter 7

The Effects of Rapid Cooling on the Improved Surface Properties of Aluminium Based Coatings by Direct Laser Deposition

Olawale Samuel Fatoba,
Mamookho Elizabeth Makhatha and
Esther Titilayo Akinlabi

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.71698

Abstract

The deterioration of materials during industrial application poses a serious threat to the materials structural integrity. A material's susceptibility to wear and surface damage can be reduced by alteration of its surface chemistry, morphology and crystal structure. Therefore, modification of surface properties plays an important role in optimizing a material's performance for a given application. Modern industrial applications require materials with special surface properties such as high hardness, wear and corrosion resistance, therefore materials engineers are vital to regularly examine how the microstructure of a material can be altered. Aluminium-based alloys have a wide application in the automotive, domestic and aerospace industries due to their excellent mechanical properties such as good weldability, sound castability and outstanding resistance to corrosion. The purpose of this research is to enhance inherent properties of the materials to create new products or improve on existing ones. The most effective engineering solution to prevent or minimize such surface region of a component is done by fibre lasers. It was concluded that Hypereutectic Al-Si alloys having transition metals are exceptional materials due to their specific properties. The addition of Cu, Fe, Cr, Si, Mg and Ni to Al-based alloys can improve the mechanical properties at both ambient and elevated temperatures.

Keywords: Al-based coatings, modification, mechanical properties, laser, materials, microstructure, laser metal deposition, Ti-6Al-4 V alloy, rapid cooling

1. Introduction

Surface modification of metals has been a useful tool in the improvement of the metal's property. It is a cost-effective method that alters the surface of components rather than the whole structure.

Laser processes are advantageous because it can target a specific area of a component, even if the shape is complex. This book chapter will focus on laser processes, their parameters, and the ternary powder Al-Si to obtain a clearer understanding of the surface treatment. Surface engineering refers to the design and modification of a surface to enhance properties such as corrosion, hardness, and wear. Surface modification has been practiced to enhancing the surface properties of materials in order to better endure wear, friction, and high temperatures through coating and alloying. Although a variety of advanced materials with significant properties have been developed, however, when it concerns a surface engineering application, physical properties of materials are among other factors that need to be considered, which include practicality and cost and time consumption. Surface treatment and coating are the most effective methods to protect surfaces from fatigue and extend the life by reducing damage at contact surfaces [1–3].

1.1. Lasers

Laser is an acronym for light amplification by stimulated emission of radiation. Lasers are mechanisms that give off intense beams of light which are coherent, monochromatic, and highly collimated. The wavelength of the beam is of high purity in comparison to other light sources; hence it is monochromatic. All the photons that constitute to the laser beam have a fixed phase relationship with respect to each other. The light from a laser generally has a very low divergence; it can travel over large distances or can be focused to a very small spot with a brightness which exceeds that of the sun. Due to these properties, lasers have been applied in a wide range of industries [4].

1.2. Laser surface modification

Applications of lasers in materials processing are widely found in part refurbishment and construction of large components from structural industry to small components such as electrochemical systems [5]. Montealegre et al. [6] acknowledged the need in different industrial sectors to improve the performance of material surface for service conditions and reported this need cannot be fulfilled by the conventional surface modification methods and coatings. There are many required component parts with specifications of surface properties when it comes to industrial applications, namely, good corrosion and wear resistance as well as good hardness. Most alloys which contain these specific properties are mostly expensive, and there is a great interest in decreasing the rate of components for fulfilling these requirements. Therefore, laser surface processing has been employed as an effective technique to improve surface properties of materials. To improve surface properties of materials, a laser beam is used to heat and modify the structure and physical characteristics of a material [6, 7]. Surface engineering has been considered as an approach to modify the surface of one metal with another metal that contains higher hardness, a lower coefficient of friction than the substrate [8–10].

Compared with other methods of surface modification, laser surface processing is characterized by the possibility of forming alloys of nonequilibrium compositions, formation of a fine microstructure, development of a strong metallurgical bond between the surface layer and the substrate, a small heat-affected zone, and the combination of a controlled minimal

http://dx.doi.org/10.5772/intechopen.71698

dilution of the substrate by the coating materials [11]. It has major advantages of high productivity, automation worthiness, noncontact processing, elimination of finishing operation, reduced processing cost, improved product quality, and greater material utilization. These characteristics and advantages have led to increasing demand of laser in material processing [12–14].

1.2.1. Types of laser surface modifications

1.2.1.1. Laser transformation hardening

It is an autogenous heat-treating technique, which involves solid-state transformation without any melting of the material. The material absorbs the laser energy and is controlled by the absorptivity of the surface. The application is limited to alloys that can be heat treated by laser [15, 16] as shown in **Figure 1**.

1.2.1.2. Laser surface melting

This technique is performed by heating the alloy's surface with a power density high enough to create a melt pool. A small ration of the top surface material is melted and cooled rapidly; the cooling rate will depend on the thermophysical properties of the metal and the scanning speed of the laser beam as shown in **Figure 2**.

1.2.1.3. Laser surface alloying

During laser surface alloying, an additional material is added to the melt pool to improve the properties [17]. The added material mixes with the molten substrate to form a new alloy. It involves melting a thin layer of the substrate with a high-power laser and simultaneously supplying the alloying element in the form of a powder as shown in **Figure 3**.

1.2.1.4. Laser cladding

Laser cladding applies the same principle as laser surface alloying, but the difference is the depth of the substrate that was melted. It enables the cladding material to be well bonded to the substrate without much mixing between them, which results in a relatively thick and homogenous overlay of coating material on the substrate as shown in **Figure 4**.

Figure 1. Schematic diagram showing the heat-affected zone of laser transformation hardening [10].

Figure 2. Schematic diagram illustrating the heat-affected zone and melt zone created by laser surface melting [15].

Figure 3. Schematic diagram displaying laser surface alloying [15].

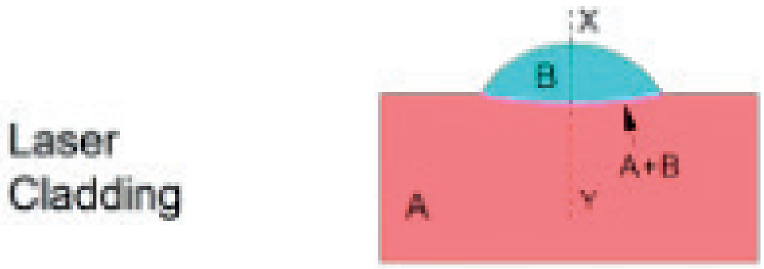

Figure 4. Schematic diagram of laser cladding [15].

1.2.1.5. Laser dispersion

It is used for forming surface composites. This technique injects hard second phase into a melted substrate. To keep the hard particles from melting, decreasing the power or exposure time is necessary. These particles remain solid during processing and after solidification of the melted substrate; the particles are dispersed in a matrix on the substrate as shown in **Figure 5**.

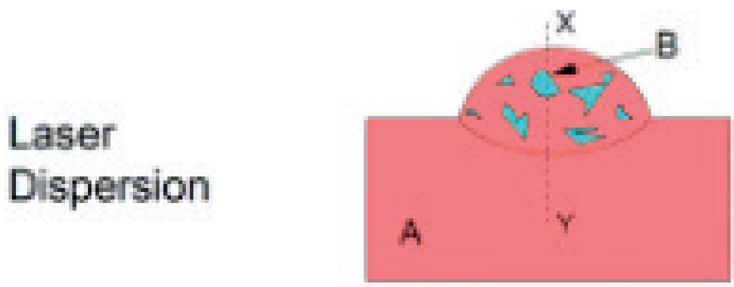

Figure 5. Schematic diagram showing the surface metal matrix formed by laser dispersion [15].

2. Overview on application and improved properties of laser-deposited Al-Si alloy coatings

Grigoriev et al. [18] studied the hypereutectic Al-Si alloys formed by laser surface treatment. Hypereutectic Al-Si alloys are being used in the manufacturing of automotive components and tools. It had been noticed that when the Si content increases, the wear resistance of these alloys increases as well. However, the Si content should not exceed 20 wt.% in standard casting processes because large primary Si particles are formed and they result in the reduction of the alloys' mechanical properties. The alloys that were to be produced had a Si content of 30, 40, and 60% (AlSi30, AlSi40, and AlSi60, respectively). The substrate used was a commercial aluminum alloy (AA6060), which composed of 0.3–0.6 wt.% Si, 0.35–0.6 wt.% Mg, 0.1–0.3% Fe, and the balance being Al. For the coat deposition, a continuous Yb:YAG 1 kW disk laser was used, and argon gas was used as the shielding gas. After processing, the samples were prepared for metallographic observation by cold mounting, polishing, and etching. To study the microstructure, optical microscopy was used, and SEM-ES was used to investigate the chemical composition of the cladding. The phases were analyzed by means of XRD, and the hardness was evaluated. The results showed that the primary Si particles in the AlSi30 were extremely fine and made it impossible to differentiate primary Si from eutectic Si in the cladding as shown in **Figure 6**. It was found that bigger primary Si particle was formed with an increase in the powder feed rate and a decrease in the laser power. The hardness of AlSi30 decreased to $HV_{0.05}$ 80 from $HV_{0.05}$ 190 which was observed from the substrate as shown in **Figure 7**.

Ma et al. [19] studied the phase and microstructure formed in Al-20Si-5Fe-3Cu-1 Mg manufactured by selective laser melting (SLM). The automotive and aerospace industries have encouraged the improvement of advanced materials with low coefficient of thermal expansion, low density, high specific strength, and excellent resistance to wear and corrosion. Hypereutectic Al-Si alloys having transition metals are exceptional materials due to their specific properties. The addition of Cu, Fe, Cr, Mg, and Ni to Al-Si alloys can improve the mechanical properties at

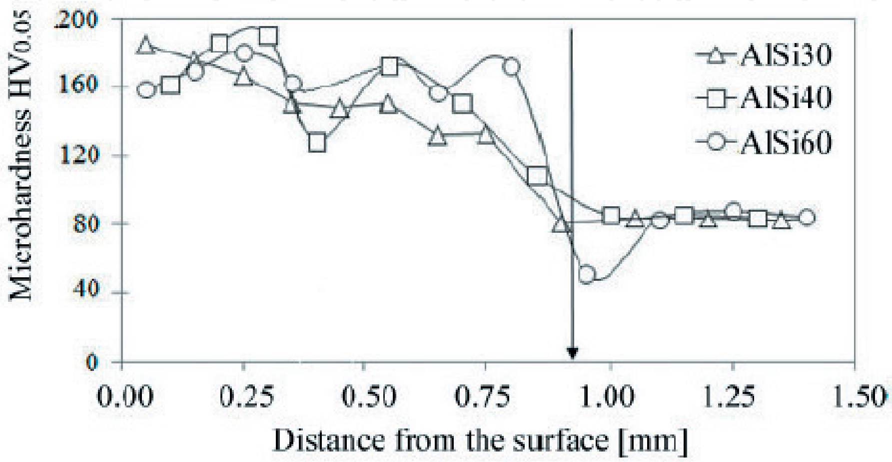

Figure 6. Microstructure of powders with different silicon contents [18].

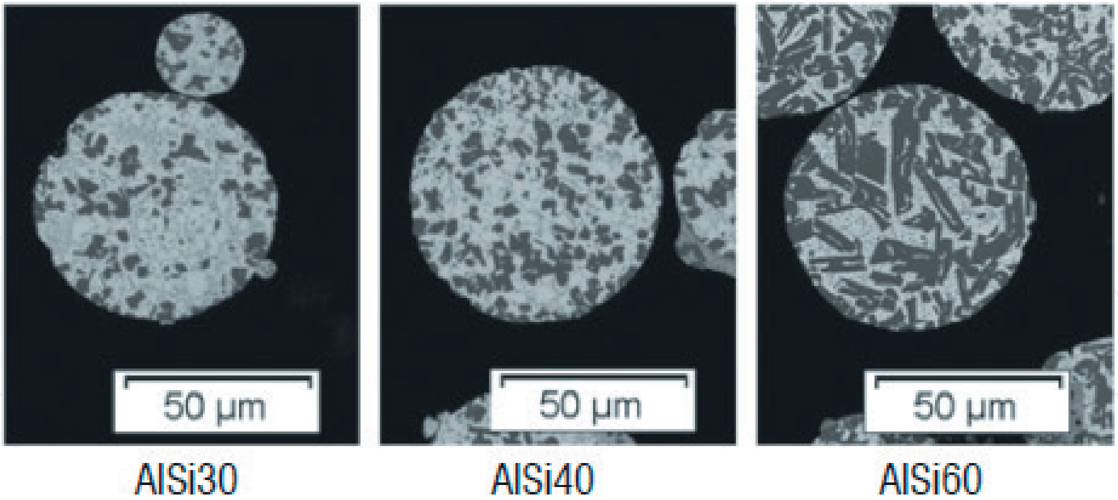

Figure 7. Microhardness distribution of laser cladding produced from alloys with different Si contents [P = 400 W, V = 800 mm/min] [18].

both ambient and elevated temperatures. The evolution of the microstructure and phase transformation of selective laser-melted Al-Si-Fe-Cu-Mg alloy that underwent different heat treatment was investigated. To manufacture the alloy, An SLM device equipped with an Yb:YAG laser was employed. The shielding gas used for the processing was high purity argon. SEM equipped with energy dispersive X-ray spectroscopy (EDS) was used to characterize the microstructure. XRD was used to analyze the present phases after SLM. The results revealed that SLM refined the primary silicon and Al-Si-Fe compound in addition to changing the morphology of eutectic silicon from a rod-like form to a mixture of dendrite and particle. The size of the SLM manufactured Al-Si-Fe compound phase reduced 4.5 times in comparison to the cast alloy (from 10.8 to 2.4 μm). The phase analysis from XRD showed that after SLM, only δ-Al_4FeSi_2 phase was present, but after heat treatment, both δ-Al_4FeSi_2 and β-Al_4FeSi_2 phases were found. It was observed that during cooling, no quasi-peritectic reaction ($L + \delta \rightarrow Si + \beta$) occurred. It can be concluded that selective laser melting of Al-20Si-5Fe-3Cu-1 Mg is better than casting the alloy.

Zhao et al. [20] studied a coating composed of Fe-Al-Si in situ composite synthesized by laser cladding. ASTM A283Gr.D steel is used in the industry as a structural material but has low wear resistance. Dispersion of a hard phase in the matrix of the coating has received interest due to the enhancement of wear resistance and microhardness. To investigate the effect of process parameters on the properties of the steel, laser cladding with Fe-Al-Si powder was done. The powder was preplaced on the steel substrate, and a continuous transverse flow CO_2 laser system was used. The parameters that were changed throughout the work were the composition of the powders, the laser power, as well as the scanning speed. After cladding, the samples were cut, and a Vickers hardness tester was used for the evaluation of the microhardness. The phase and microstructure were studied with XRD and SEM, respectively. A wear tester was used to characterize the wear resistance. The results showed that Fe, SiO_2, and $Al_2Fe_3Si_4$ intermetallic compound were formed on the surface of the steel substrate. It was observed that the increase in the laser power increases the wear resistance up until the power of 1600 kW and beyond this power, the wear resistance decreases. The increase in the scanning speed, until the speed of 400 mm/min, caused the wear resistance of the coating to

http://dx.doi.org/10.5772/intechopen.71698

increase. The hardness of the coating increased with the increased of the power and scanning speed until their peaks were reached. It was seen that the increase in laser power and scanning speed refined the grain size of the coating.

Kempen et al. [21] investigated the mechanical properties of AlSi10Mg manufactured by selective laser melting. Aluminum-silicon alloys have a wide application in the automotive, domestic, and aerospace industries due to their excellent mechanical properties such as good weldability, sound castability, and outstanding resistance to corrosion. Selective laser melting of the alloy can offer a wider range of application, such as structures that are complex involve cavities. To manufacture the alloy, the AlSi10Mg powder was processed using a modified concept laser M1 SLM machine, which is equipped with a 200 W fiber laser. A polarizing microscope and scanning electron microscope were used to observe the microstructures formed. The hardness was determined by means of a Vickers hardness tester, and X-ray patterns were measured with a goniometer. The results revealed that the AlSi10Mg parts produced by selective laser melting exhibited better overall mechanical properties when compared to the casted AlSi10Mg material shown in **Figure 8**. The improvement of these properties was attributed to the formation of $MgSi_2$, the rapid cooling rate resulted in a very fine microstructure, and the distribution of the Si phase was found to be fine as well. The fine microstructure consisted of tiny Al-matrix cells/dendrites (**Figure 9**) decorated with silicon phase. It was therefore concluded that selective laser melting of AlSi10Mg gives rise to mechanical properties than conventional casting.

Lijing et al. [22] examined the microstructure and hardness of selective laser melted of Al-8.5Fe-1.3 V-1.7Si alloy. Al-Fe-V-Si alloys show a great chance in being a competitive alternative to titanium alloys in the aerospace industry; this is due to their ductility, high strength, rapid solidification, and toughness at elevated temperatures. Vacuum induction melting in an argon atmosphere was used to produce the substrate which composed of Al-8.5Fe-1.3 V-1.7Si. A DEYU LM 200 SLM instrument equipped with Yb:YAG fiber laser was for SLM in an argon atmosphere. To observe the effect of scanning speed on the properties, two speeds were used: 200 and 250 mm/s. For microstructural analysis, an electron probe micro-analyzer (EPMA), transmission electron microscopy (TEM) equipped with energy dispersive X-ray spectroscopy (EDS) was used. XRD was used to perform phase analysis, and a Vickers hardness tester was used to establish the microhardness. It was found that SLM-processed samples composed of α-Al,

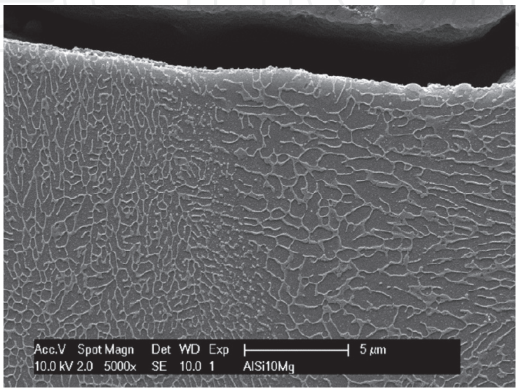

Figure 8. Fracture surface of a SLM-produced AlSi10Mg sample. The border of the broken test sample is shown, where the borderline porosity initiated cracks toward the side of the sample [21].

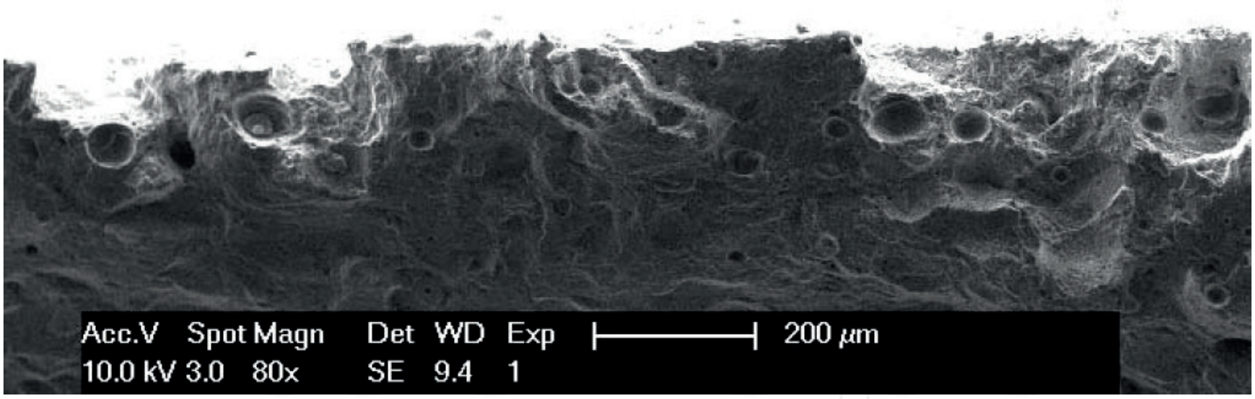

Figure 9. SEM micrograph of a AlSi10Mg SLM part showing the Al-matrix cells decorated with Si phase. A cross section perpendicular to the layers and the scanning direction [21].

$Al_{12}(Fe,V)_3Si$, and θ-$Al_{13}Fe_4$ phases. The laser-melted zone displayed a region of a mixture zone of α-Al and nanoscale $Al_{12}(Fe,V)_3Si$ or a cellular-dendritic structure, the melt pool border was found to have submicron θ-$Al_{13}Fe_4$ particles, and the heat-affected zone had an identical mixture zone of $Al_{12}(Fe,V)_3Si$ and α-Al. The hardness of the SLM-processed samples was much higher than that of the cast alloy. The hardness of the sample processed with a scanning speed of 200 mm/s was found to be in the range of 145–175 HV and 135–170 HV was the range of hardness for the scanning speed of 250 mm/s, and the hardness of the cast alloy was 40–45 HV. It can be concluded that SLM gives better surface properties than casting.

Anandkumar et al. [23] analyzed the sliding wear resistance and microstructure of an Al-12 wt. % Si/TiC laser clad coating. Al-alloy matrixes (Al-MMCs) have excellent mechanical properties, good wear resistance, and low density and have found application in automotive or aerospace industries. SiC has been extensively used for the reinforcement of Al-MMCs, but it dissolves significantly in molten aluminum; this results in the precipitation of Al_4C_3 at temperatures of 670–1350°C. The coating produced was composed of 40 wt.% TiC powder, and the balance was Al-12wt.% Si powder. The powders were mixed with a Turbula powder mixer. For the laser cladding, a continuous wave Nd:YAG laser system was used to clad the powder on Al–7 wt.% Si cast alloy plates. The laser power used was 1.8 kW, and the scanning speed was 12 mm/s. After laser cladding, the samples were prepared for analysis by standard metallographic polishing methods and then followed by etching with Keller's reagent. To characterize the microstructure, optical microscopy, scanning electron microscopy, energy dispersive X-ray spectroscopy, and X-ray diffraction were used. A Vickers hardness tester was used to determine the microhardness, and the dry sliding wear tests were performed with a ball-cratering apparatus. The results showed that the microstructure of Al-12wt.%Si/TiC coatings had TiC particles distributed in a matrix that consisted of 35 vol.% primary α-Al dendrites and interdendritic α-Al + Si eutectic. Because of partial dissolution of TiC in liquid aluminum, 3% of Ti_3SiC_2 was found to be present in the coating. The hardness of the coating was determined to have increased to 165 HV from the hardness of 115 HV exhibited by the substrate. The wear coefficient of the Al-Si/TiC composite was lower than that of the Al-12wt.% Si alloy and the substrate. The 2.2 mm^3/Nm was found to be the wear coefficient of the composite, 8.2 mm^3/Nm was determined for the alloy, and the substrate presented a

http://dx.doi.org/10.5772/intechopen.71698

wear coefficient of 4.5 mm^3/Nm. Hence, it was concluded that the coating produced by laser cladding had superior mechanical properties.

Zhao et al. [24] studied ultrafine Al-Si hypereutectic alloy produced by direct metal deposition. Hypereutectic Al-Si alloys are being applied in the automobile, aeronautical, and military industries because of their good corrosion resistance, low density, low thermal expansion coefficient, good casting ability, and high wear resistance. The large proportions of coarse primary Si present in Al-Si alloys formed during conventional casting processes can decrease their anti-wear characteristic and ductility; to overcome this, the primary Si of the alloy should be refined. The substrate used was 6061 aluminum alloy which was prepared by sandblasting, and Al-Si and silicon carbide powders were used. A direct metal deposition machine was used to deposit 10 successive layers by scanning the laser back and forth over the previous layer. A coaxial nozzle was used to inject the powders at a feed rate of 4.9 g/min. The samples were cut along the transverse section and were prepared by metallographic polishing and etching in Keller's reagent. SEM-EDS was used to characterize the microstructure of the layer, XRD was used to determine the phases present, and an automatic microhardness tester was used to evaluate the microhardness. The results showed that an in situ hypereutectic Al-Si alloy containing primary Si is ultrafine. It was observed that an increase in the scanning speed and laser power led to an increase in the volume fraction of primary Si, as well as the size. The size of eutectic Si grain decreased with the increase in scanning speed and reached the minimum value at a laser power of 850 W. the microhardness tests displayed that an increase in scanning speed resulted in an increase in the microhardness. It was concluded that direct metal deposition refined the microstructure and, therefore, resulted in improved properties.

Li et al. [25] examined the effect heat treatment had on AlSi10Mg alloy manufactured by selective laser melting. AlSi10Mg is extensively used in automotive and aerospace industries and heat exchanger products. The wide range of application is due to the high mechanical properties, low thermal expansion, reduced recycling costs, and light weight of this alloy. It has been revealed that in a tensile environment, coarse and acicular eutectic silicon phases instigate cracks, which in turn brings about the deterioration of mechanical properties. The modification of this coarse phase is important in improving the mechanical properties of AlSi10Mg alloy. The alloy was produced with a gas-atomized powder processed with a selective melting machine where the parameters were a scanning speed of 1140 mm/s, a laser power of 350 W, scan spacing of 170 μm, and a powder layer thickness of 50 μm. During selective laser melting, argon gas was used as a shielding gas. After SLM, the samples were subjected to solution heat treatment at different temperatures (450, 500, and 550°C) for 2 h and water quenched. Half of the samples were exposed to artificial aging at 180°C for 12 h. Prior to characterization, the samples were ground, polished, and etched in Keller's reagent. SEM was used to examine the microstructure, and XRD was used to analyze the phases present. A high-precision electronic universal testing machine was used for tensile tests, and a Vickers hardness tester was used to get the microhardness. The results showed that the solubility of Si atoms in Al matrix rapidly decreased with the increase in the heat treatment temperature, and after aging the solubility decreased even further. An ultrafine eutectic microstructure was formed as a result of the high cooling rate and thermal fluctuation of selective laser melting;

this led to significantly improve tensile properties and hardness. The size of Si particles was initially small after SLM but coarsened with heat treatment and become coarser with aging.

Gu and Van Gelder [26] characterized the coating layer of laser-deposited Al-Si over laser weld bead as shown in **Figures 10** and **11**. Steel sheets in the automotive industry should have excellent corrosion resistance as it is the primary protection of these sheets. The weld bead was prepared by applying a localized coating by means of well-defined spot heating and concurrently spraying coating material powder (Al-Si) on the heated spot. A Trump disk was used to perform laser welding and laser-localized coating. A steel sheet was used as the substrate. After processing, the samples were water quenched. Scanning electron microscopy coupled with energy dispersive spectroscopy was used to characterize the morphology of the coating layer. The results showed that the thickness of the layer varied from 100 to 140 μm depending on the feed rate, laser power, and processing speed. A thin layer was produced by a faster speed and lower power. EDS revealed that the layer consisted of Fe-rich intermetallic compound as also reported by [27, 28]. For a higher laser power, Fe-Al and Fe_3Al phases were present, and for a lower energy and fast process, Fe-Al, Fe_3Al, and α-Fe intermetallic phases were identified. The coating was found to be a stable Fe-Al compound enriched with Fe which would provide improved corrosion resistance for the steel material underneath it.

Liang et al. [29] studied the corrosion resistance and high strength of an Al-Si-based casting alloy. Because Al-Si-based casting alloys exhibit good castability, great strength-to-weight ratio, and reduced manufacturing costs, they have a variety of applications in the automotive industries. Although these properties are desirable, the alloys were stated to have a high corrosion rate in environments that contained salt. Alloying was a technique employed to improve the properties. The two reference metals used composed of silicon, iron, copper, manganese, magnesium, zinc, and aluminum of different compositions, and the new alloy has the same

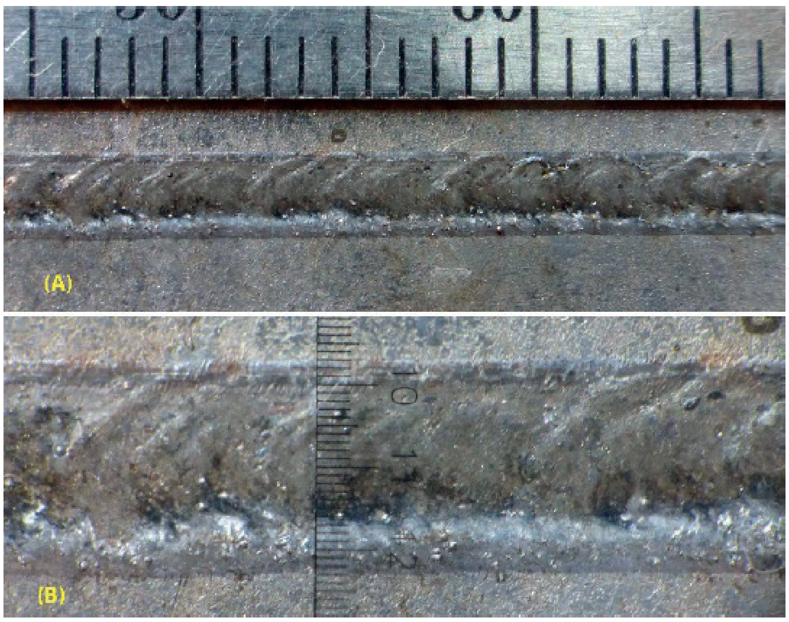

Figure 10. Top view of a laser-generated coating on weld bead [26].

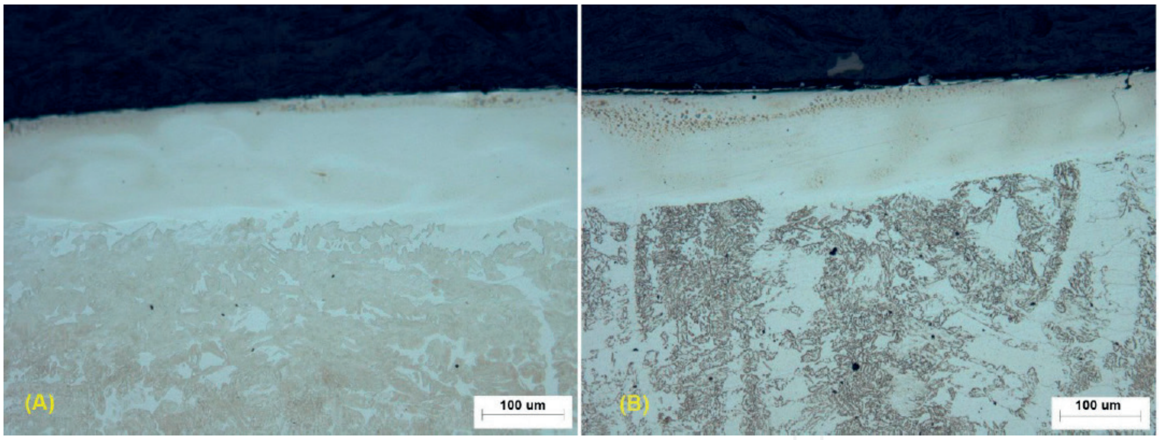

Figure 11. Optical micrographs of the coating before (A) and after (B) heat treatment [26].

metals with an addition of strontium. The metals were melted in clay graphite crucibles heated at 740°C and poured into a steel mold, and then the ingots were aged at 180°C for 4 h before they were allowed to cool be undergo analysis. Tensile tests were done, the microstructures were assessed using optical and scanning electron microscopy, and the corrosion behavior was evaluated by means of immersion tests and polarization. XRD was used to observe the surface of the samples before and after immersion tests were done in a 3.5 wt. % NaCl solution for 240 h. The microstructural tests revealed that all three alloys had an intermetallic that contained eutectic silicon, α-Al dendrites, and needle-shaped Fe. The addition of strontium made the α-Al dendrites of the new alloy more uniform and columnar than those of the reference alloys. The tensile tests revealed that the new alloy had a higher strength and could be elongated; this was due to the eutectic silicon being more spherical and much finer. The corrosion tests revealed that all three alloys had the same corrosion mechanism, but the new alloy had a much higher corrosion resistance. The XRD performed after immersion tests showed that the new alloy had fewer sites of pit corrosion. The authors therefore conclude that the new alloy has superior microstructural and mechanical properties (**Figure 12**).

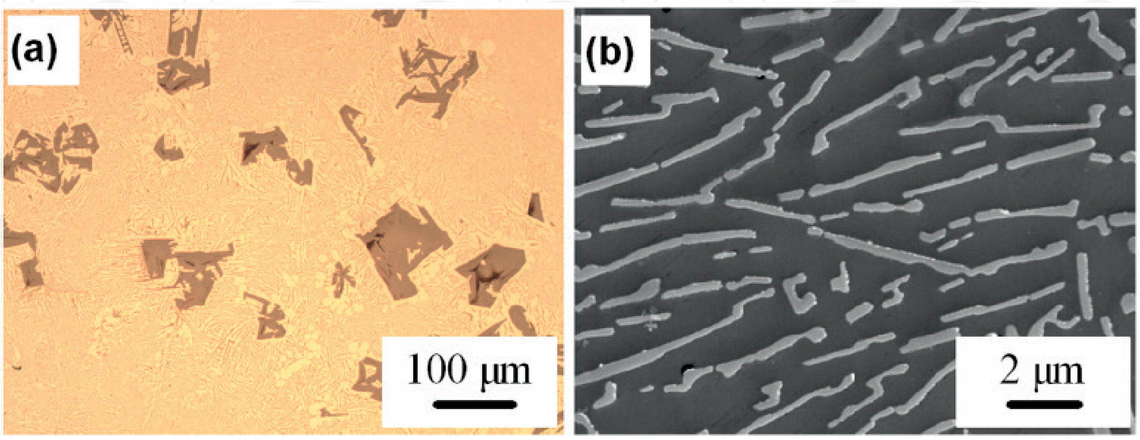

Figure 12. (a) Microstructure of as cast Al-20Si alloy and (b) high magnification micrograph showing the eutectic Al-Si [24].

El-Salam et al. [30] analyzed how the mechanical and structural properties of Al-Si alloy were affected by the Sn content. Al-Si cast alloying is mainly used for applications such as automobile components and instrument panels in the transportation industries. Tin has outstanding anti-welding properties with iron and low strength and modulus; this makes it a crucial component in bearing. Adding Sn to Al-Si or adding Si to Al-Sn produces the possibility of meeting the requirements needed for maintaining a balance of strength and soft surface characteristics. Different amounts of Sn (0.5–2 wt.%) were added to Al-3 wt.% Si alloy to observe the effect. The samples were made by melting 99.99% pure Al, Sn, and Si in a graphite crucible at different compositions, and the ingots were normalized at 550°C for 53 h. The hardness and stress-strain were tested as well as the microstructure of the alloys by means of a transmission electron microscope. The stress-strain curves obtained for the alloys show that the hardness of the alloys decreases when the temperature increases and increases when the Sn content is raised as also reported by Makhatha et al. [2017]. After homogenization, it was found that the spheroidized Si particles were encased in β-Sn layers that formed a peritectic structure. The ternary alloy, Al-Sn-Si, had overall better mechanical properties in comparison to the initial binary alloy Al-Si. The authors therefore conclude that the addition of Sn to Al-Si alloys enhances the mechanical properties of the alloys and a higher Sn content leads to an alloy with superior alloys.

Kang et al. [31] studied the microstructure of hypereutectic Al-Si alloys produced by means of selective laser melting (SLM), as well as its wear behavior. Aluminum alloys have numerous applications in the automobile and aircraft industries due to their excellent properties such as corrosion resistance, formability, and high stiffness-to-weight ratio. Al-Si alloys have a low thermal expansion coefficient and a high strength to weight ratio and resist wear; these properties allow the alloy to be used as a material for pistons and engine blocks. It has been observed before that the increase of silicon content until eutectic constitution will increase the resistance to wear of the alloys. An investigation was done on the impact that laser power had on the microstructure and mechanical properties of the alloy. The powders were mixed, and a commercial SLM machine was used to fabricate the alloy on an aluminum base plate at laser powers that ranged from 120 to 225 W. The microhardness of the samples was obtained by employing a Vickers pyramid, the microstructure was observed using optical microscopy and SEM-EDS, and dry ball-on-disk wear tests were done on the samples. After the tests were conducted, it was found that relatively packed hypereutectic Al-SI alloys were achieved in situ from a combination of elemental powders using a SLM procedure under argon conditions. The microhardness and relative density increased with the increase of power until 210 W; beyond this power, the mechanical properties reduced drastically. Analyzing the microstructure revealed that the increase of laser power caused the porosity of the samples decrease and the form of pores altered from an irregular shape to a spherical one. The authors therefore concluded that a laser power of 210 W was the optimum to use as it presented the highest relative density and microhardness and exhibited the lowest wear rate of all the processed specimens.

Zhao et al. [32] studied in situ composite coating Fe-Al-Si that was fabricated by laser cladding. Steel has many applications, but its poor wear resistance limits the extent of which it can be used. The intermetallic compound Fe-Al has good corrosion resistance and reasonable wear resistance and can be fabricated by laser processing to improve surface properties. The effect of powder consumption, scanning speed, and laser power on the wear resistance, microhardness, and microstructure was examined. The substrate used was ASTM A283Gr.D steel, and the coating applied was a composite powder consisting of Fe-Al-Si. The powder was preplaced onto the substrate, and the laser equipment used was a continuous CO_2 laser. The parameters that were changed were the ratios of the powders, the laser power, and the scanning speed of the laser beam. Once the laser processing was complete, the samples were cut, and the hardness was obtained by using a Vickers microhardness tester, the wear resistance was assessed by means of a wear tester, and the microstructure and phases were examined using SEM and XRD, respectively. The intermetallic compound found in the in situ coating was $Al_2Fe_3Si_4$, and it existed with Fe and SiO_2. The grain size of the coating was revealed to decrease with the increase of the scanning speed and laser power of the beam used. When the scanning speed and power of the laser increased, it caused the microhardness to increase; it increased to three times that of the substrate. The wear tests showed that the increase of the laser parameters increased the wear resistance of the coating; the wear resistance of the coating was 3.5 better than the substrate. It can be concluded that the Fe-Al-Si in situ composite coating had enhanced properties in comparison the ASTM A283Gr.D steel.

Ma et al. [33] investigated how the mechanical properties of Al-20Si synthesized by selective laser melting were influenced by annealing. Aluminum-based alloys are applied as lightweight structural materials due to their low density and high strength. Hypereutectic Al-Si alloys have a variety of applications in the aerospace and automobile industries as a result of their high resistance to wear and corrosion, low density, good machinability and thermal conductivity, and high thermal stability. Research on SLM processing of Al-Si alloys mainly focus on the hypoeutectic regime and not enough on the hypereutectic. A selective laser melting device equipped with Nd-YAG laser was used to prepare Al-20wt.% Si samples in a form of cylindrical tensile bars. The powders used were gas atomized. During the laser processing, argon gas was used as a shielding gas. An Al-20Si alloy was casted by graphite mold casting for comparison. The samples were then subjected to heat treatment by annealing. Optical microscopy and scanning electron microscopy equipped with energy dispersive spectroscopy were used for the microstructural characterization of both the SLM and cast alloys. The phases were analyzed by XRD, and testing device was used to test the strain of the samples as part of the tensile tests. The results displayed that the size of the eutectic and particulate Si was refined when SLM processing was employed. With the increase in the annealing temperature, the Si particles became coarser. The strength of the SLM Al-20Si was higher than those produced by different techniques (**Table 1**).

Viswanathan et al. [34] analyzed TiC-$Al1_3Fe_4$ composite layer formed on Al-Si alloy by laser processing. Cylinder blocks, pistons, valve lifters, and cylinder heads are often made of Al-Si alloys due to their good corrosion resistance, great formability, high thermal conductivity, high specific strength, and low density. The limitation of being used in other industrial applications is because of the poor wear resistance and low hardness. The substrate used was Al-12% Si with a composition of 12 wt.% Si, 1 wt.% Fe, 1.5 wt.% Cu, 1.5 wt.% Mg, 1.5 wt.% Ni, 0.2 wt.%Ti, and the remainder being Al. Two different coatings were applied on the substrate: 75–25% TiC-Fe (Coating A) and 25–75% TiC-Fe (Coating B). The laser processing was done using a continuous wave CO_2 laser where argon was used as shielding gas. After coating, the samples were sectioned and prepared for metallographic examination. The microstructure

Preparation methods	YS (MPa)	UTS (MPa)	Ductility (%)
As cast-1	105	162	4.6
As cast-2	95	120	0.37
As cast-3	—	91.5	0.49
Ultrasonic treated	80	130	1.2
Extruded-1	155	190	3.6
Extruded-2	—	280	>30
Extruded-2 + ECAP	—	350	>30
RS + wrought	131	210	19.7
As cast-1 + wrought	118	177	7.7

Table 1. Tensile properties of Al-20Si alloys processed by different methods (YS = yield strength; UTS = ultimate tensile strength) [24].

was assessed using an optical microscope, the hardness was obtained using a microhardness tester with a load of 100 g, the phases were evaluated by means of XRD, and the wear was tested using a block-on-ring dry sliding wear tribometer. The tests revealed that a different type of iron-based aluminum phase, $Al_{13}Fe_4$, was formed during laser processing. The sample from Coating A exhibited good metallurgical bonding between the coating and the substrate, whereas Coating B did not form a layer, but it dissolved into the substrate. Coating A had an even hardness distribution all over the composite layer and had a hardness that was about six times higher than that of the substrate. The TiC reinforced with $Al_{13}Fe_4$ led to a reduced wear rate of the composite layer. It can be concluded that the higher TiC content will enhance the tribological properties of Al-Si alloys.

Chen et al. [35] investigated laser cladding of Al-Si powders on a magnesium-based Mg-Gd-Y-Zr alloy. The effect of scanning speed on the properties of the surface was also examined. Alloys based on magnesium are extensively used in industries such as aerospace and automobile due to their good castability and machinability, high strength, and low density. The range of application of magnesium alloys is limited by their low corrosion resistance and poor resistance to wear. The substrate was a magnesium-based Mg-Gd-Y-Zr alloy that was casted and homogenized for 12 h at a temperature of 500°C; it was then sectioned, polished with alumina sand papers, and rinsed with pure ethanol. The powders were mixed at a weight ratio of 3:1 (Al to Si) and were placed on the substrate homogenously and were pressed to expel the gas between the particles of the powder. For laser cladding, a continuous carbon dioxide gas laser was used, and the shielding gas applied was high purity argon. The clad samples were polished and etched; then SEM was employed to analyze the microstructure of the cross section of the sample. The phase constituents of the clad layers were studied using XRD and the microhardness on the cross section of the samples was done with a microhardness tester, and a load of 50 g was used. The potentiodynamic polarization was measured by means of a three-electrode cell in an aqueous solution of 3.5 wt.% NaCl. Before the corrosion tests were done, the samples were polished and cleaned with ethanol. The clad layer was found to be made up of Mg, $Mg_{17}Al_{12}$ phases, Mg_2Si, and isolated Al_2 (Gd, Y) particles. It was concluded that these intermetallic composites were responsible for the strengthening of the clad layer. The highest microhardness was achieved with the slowest scanning speed because it had a deeper hardened layer. The corrosion resistance of the laser clad layer was much higher than that of the substrate.

3. Conclusion

The main aim of this study is to show the improved properties of Al-Si alloy by laser metal deposition by developing high wear and corrosion-resistant coatings using various combinations of laser metal deposition powders as reinforcements. From the literature reviewed, all authors agreed that the Ti6Al4V alloy has poor wear resistance as well as low hardness property, thus having the tendency to gall. From the reviewed literature, it can be concluded that laser surface modification techniques have the ability to improve the microstructure, mechanical, and tribological properties of Ti6Al4V alloy.

The reviewed literature indicates that laser cladding can be employed as a technique that will improve the surface properties. It refines the microstructure of the alloy, therefore improving mechanical properties. The corrosion resistance can be bettered by adding other elements to the surface of the material.

Author details

Olawale Samuel Fatoba[1]*, Mamookho Elizabeth Makhatha[1] and Esther Titilayo Akinlabi[2]

*Address all correspondence to: drfatobasameni@gmil.com

1 Department of Mechanical Engineering Science, Faculty of Engineering and the Built Environment, University of Johannesburg, South Africa

2 Department of Metallurgy, Faculty of Engineering and the Built Environment, University of Johannesburg, South Africa

References

[1] Ching HA, Choudhury D, Nine MJ, Abu Osman NA. Effects of surface coating on reducing friction and wear of orthopaedic implants. Science and Technology of Advanced Materials. 2014;**15**(1):1-7

[2] Bacci T, Pradelli G, Tesi B, Gianoglio C, Badini C. Surface engineering and chemical characterization in ion-nitrided titanium and titanium alloys. Journal of Materials Science. 1990;**25**:4309-4314

[3] Dressler S. Plasma treatments. In: Sudarshan TS, editor. Surface Modification Technologies: An Engineer's Guide. New York: Marcel Dekker; 1989. pp. 317-419

[4] Toma M. Laser fusing of alloy powders for applying hard facing layers onto mild steel substrate. Damascus University Journal. 2005;**21**(2):95-117

[5] Bao R, Yu H, Chen C, Qi B, Zhang L. Development of laser cladding wear resistant coating on titanium alloys. Surface Review and Letters. 2006;**13**:645-654

[6] Montealegre MA, Castro G, Rey P, Arias JL, Vanquez P, Gouzalez M. Surface treatments by laser technology. Contemporary Materials. 2010;**I-1**:19-30

[7] Fatoba OS, Popoola API, Aigbodion VS. Experimental study of hardness values and corrosion behaviour of laser alloyed Zn-Sn-Ti coatings of UNS G10150 mild steel. Journal of Alloys and Compounds. 2016a;**658**:248-254

[8] Baker TN. (2010) Laser surface modification of Ti alloys. In: Surface Engineering of Light Alloys - Aluminium, Magnesium and Titanium Alloys. Cambridge, UK: Woodhead Publications; 2010. pp. 398-443. ISBN 1-84569-537-2. https://strathprints.strath.ac.uk/8071/

[9] Popoola API, Fatoba OS, Aigbodion VS, Popoola OM. Tribological evaluation of mild steel with ternary alloy of Zn-Al-Sn by laser deposition. International Journal of Advanced Manufacturing Technology. 2016a:1-7. DOI 10.1007/s00170-016-9170-7

[10] Fatoba OS, Popoola API, Pityana SL, Adesina OS. Computational dynamics of anti-corrosion performance of laser alloyed metallic materials. Paul M. ed. Fiber Laser; 2016: InTech. DOI: 10.5772/62334. Available from: http://www.intechopen.com/books/fiber-laser/computational-dynamics-of-anti-corrosion-performance-of-laser-alloyed-metallic-materials

[11] Fatoba OS, Popoola API, Fedotova T, Pityana SL. Electrochemical studies on the corrosion behaviour of laser alloyed Zn-Sn coatings on UNS G10150 steel in 1M HCl solution. Silicon. 2015a;**7**(4):357-369

[12] Lo KH, Cheng FT, Kwok CT, Man HC. Improvement of cavitation erosion resistance of AISI 316 stainless steel by laser surface alloying using fine WC powder. Surface and Coatings Technology. 2003;**165**:258-267

[13] Oberlander BC, Lugscheider E. Comparison of properties of coatings produced by laser cladding and conventional methods. Materials Science and Technology. 1992;**8**:657-665

[14] Adebiyi DI, Fatoba OS, Pityana SL, Popoola API. Parameters optimization, microstructure and microhardness of silicon carbide laser deposited on titanium alloy. In: Proceedings of International Conference on Surface Modification Technologies, 29th June-1st July, 2016, Milan, Italy; 2016. pp.1-6

[15] Kwok CT, Cheng FT, Man HC, Ding WH. Corrosion characteristics of nanostructured layer on 316L stainless steel fabricated by cavitation-annealing. Journal of Materials Letters. 2006;**60**:2419-2422

[16] Popoola API, Fatoba OS, Popoola OM, Pityana SL. The influence of heat treatment and process parameter optimization on hardness and corrosion properties of laser alloyed X12CrNiMo steel. Silicon. 2016;**8**(4):579-589

[17] Fatoba OS, Popoola API, Fedotova T. Characterization and corrosion behaviour of Zn-Sn binary alloy coatings in 0.5M H_2SO_4 solution. Journal of Electrochemical Science and Technology. 2015;**6**(4):65-74

[18] Grigoriev SN, Tarasova TV, Gvozdeva GO, Nowotny S. Structure formation of hypereutectic al-Si-alloys produced by laser surface treatment. Journal of Mechanical Engineering. 2014;**60**:389-394

[19] Ma P, Jia Y, Prashanth KG, Scudino S, Yu Z, Eckert J. Microstructure and phase formation in al-20Si-5Fe-3Cu-1Mg synthesized by selective laser melting. Journal of Alloys and Compounds. 2016;**657**:430-435

[20] Zhao L-Z, Zhao M-J, Li D-Y, Zhang J, Xiong G-Y. Study on Fe–al–Si in situ composite coating fabricated by laser cladding. Applied Surface Science. 2012;**258**:3368-3372

[21] Kempen K, Thijs L, Van Humbeeck J, Kruth J-P. Mechanical properties of AlSi10Mg produced by selective laser melting. Physics Procedia. 2012;**39**:439-446

[22] Lijing Z, Yingying L, Shaobo, Hu Z. Selective laser melting of al–8.5Fe–1.3V–1.7Si alloy: Investigation on the resultant microstructure and hardness. Chinese Journal of Aeronautics. 2015;**28**:564-569

[23] Anandkumar R, Almeida A, Vilar R. Microstructure and sliding wear resistance of an al–12 wt.% Si/TiC laser clad coating. Wear. 2012;**282-283**:31-39

[24] Zhao LZ, Zhao MJ, Song LJ, Mazumder J. Ultra-fine al–Si hypereutectic alloy fabricated by direct metal deposition. Materials and Design. 2014;**56**:542-548

[25] Li W, Li S, Liu J, Zhang A, Zhou Y, Wei Q, Yan C, Shi Y. Effect of heat treatment on AlSi10Mg alloy fabricated by selective laser melting: Microstructure evolution, mechanical properties and fracture mechanism. Materials Science & Engineering A. 2016;**663**:116-125

[26] Gu H, Van Gelder A. Coating layer characterization of laser deposited al-Si coating over laser weld bead. Physics Procedia. 2016;**83**:597-605

[27] Makhatha ME, Fatoba OS, Akinlabi ET. Effects of rapid solidification on the microstructure and surface analyses of laser-deposited Al-Sn coatings on AISI 1015 steel. International Journal of Advanced Manufacturing Technology. 2017. 1-15. https://doi.org/10.1007/s00170-017-0876-y

[28] Aigbodion VS, Popoola API, Fatoba OS. Evaluation of hardness values and corrosion behaviour of laser alloyed 20Al-20Sn-60Ti coatings of UNS G10150 mild steel. International Journal of Advanced Manufacturing Technology. 2015;**81**:1-11. DOI: 10.1007/s00170-015-8111-1

[29] Liang ZX, Ye B, Zhang L, Wang QG, Yang WY, Wang QD. A new high-strength and corrosion-resistant al–Si based casting alloy. Materials Letters. 2013;**97**:104-107

[30] Abd El-Salam F, Abd El-Khalek AM, Nada RH, Wahab LA, Zahran HY. Effect of Sn content on the structural and mechanical properties of al–Si alloy. Materials Science and Engineering A. 2010;**527**:1223-1229

[31] Kang N, Coddet P, Liao H, Baur T, Coddet C. Wear behavior and microstructure of hypereutectic al-Si alloys prepared by selective laser melting. Applied Surface Science. 2016; **378**:142-149

[32] Zhao LZ, Zhao MJ, Li DY, Zhang J, Xiong GY. Study on Fe–al–Si in situ composite coating fabricated by laser cladding. Applied Surface Science. 2011;**258**:3368-3372

[33] Ma P, Prashanth KG, Scudino S, Jia Y, Wang H, Zou C, Wei Z, Eckert J. Influence of annealing on mechanical properties of al-20Si processed by selective laser melting. Metals. 2014;**4**:28-36

[34] Viswanathan A, Sastikumar D, Kumar H, Nath AK. Laser processed TiC–$Al_{13}Fe_4$ composite layer formation on al–Si alloy. Optics and Lasers in Engineering. 2012;**50**:1321-1329

[35] Chen E, Zhang K, Zou J. Laser cladding of a mg based mg–Gd–Y–Zr alloy with al–Si powders. Applied Surface Science. 2016;**367**:11-18