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Challenges and Opportunities in the Additive Layer Manufacturing of Al-Al_2O_3 Nanocomposites

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Abstract *This work reviews the advanced engineering materials widely used in the aerospace and automotive industries, with specific emphasis on titanium, aluminium and their alloys. It shows that titanium alloys are being used extensively in aircraft engine parts, while aluminium and its alloys have found broad application areas in airframe structures and various vehicle components. Due to their superior mechanical and physical properties, aluminium matrix nanocomposites have been used in several demanding fields, and among them, Al-Al_2O_3 nanocomposites provide a lightweight material with better wear resistance and thermal stability at elevated temperatures. To produce Al-Al_2O_3 nanocrystalline powders, a high-energy ball milling process could be an effective but simple approach. A selective laser melting (SLM) process could be used to produce advanced Al-Al_2O_3 nanocomposites as it has the potential to create final parts in any complex shape but without waste. Although several challenges are inherent to this process, such as high reflectivity, high thermal conductivity and oxidation, the future of the SLM of Al-Al_2O_3 nanocomposites is promising as research continues to focus on addressing these problems.*

Keywords: Al-Al_2O_3 nanocomposite, Selective laser melting, Challenges

1. Introduction

The aerospace and automotive industries play an important role in countries' economic development. Nowadays, to be faster and safer are consistent goals of aircraft and vehicle designers. To achieve this objective, various materials have been developed that are more sophisticated, better fabricated and safer than ever before. For instance, composites, aluminium, titanium and their alloys are utilized in aircrafts and vehicles. The resultant weight reductions have improved fuel consumption and increased payloads, resulting in cost reductions. Additionally, the improved mechanical properties of these new materials have increased the period between maintenance operations and reduced repair costs. Since materials play such an important role in cost reduction, manufacturers and material producers have focused on the development of various new materials to meet customer requirements [1].

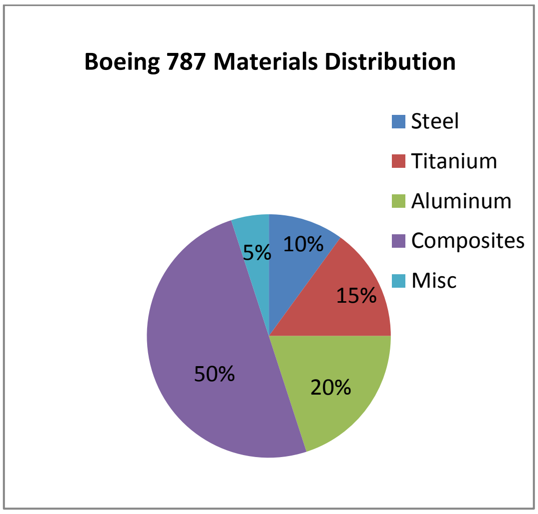
Composite materials are increasingly enjoying widespread use in the aerospace and automotive industries due to their superior mechanical and physical properties. Among them, aluminium matrix composites (AMCs) offer a comparatively light weight, greater yield strength, improved high temperature properties, wear resistance and a controlled thermal expansion coefficient. These materials have found broad application in several demanding fields like the automotive, aerospace, defence, sports, electronics and biomedical industries, as well as for other industrial purposes [2]. Moreover, compared to other reinforcements, alumina particles provide better thermal stability at high temperatures, while nanostructures yield superior properties, which is significant for engineering requirements.

On the other hand, selective laser melting (SLM) is one of the additive layer manufacturing processes used to fabricate three-dimensional parts with complex geometries and shows great potential for the manufacture of advanced engineering components [3]. However, there is relatively little research on the SLM of aluminium components owing to several challenges in the process, such as the high reflectivity of Al to short wavelength laser, poor flowability and oxidation [4]. Dadbakhsh et al. [3] investigated the effect of aluminium alloys on SLM behaviour and the microstructure of in-situ formed composites. The different contents of the alloying elements were believed to change the melting phenomenon because of the variable thermal conductivity of the alloys. Louvis et al. [5] utilized relatively low laser power to manufacture aluminium components and analyzed the mechanism of thin oxide film formation. Olakanmi [6] focused on the effects of processing conditions and powder properties on the sintering/melting of pure Al, Al-Mg and Al-Si particles. In addition, Read et al. [7] proposed a model to study the relationship between the porosity of final parts and the laser melting process parameters. It has been shown that decreasing the laser power and increasing the scan speed both result in increased porosity.

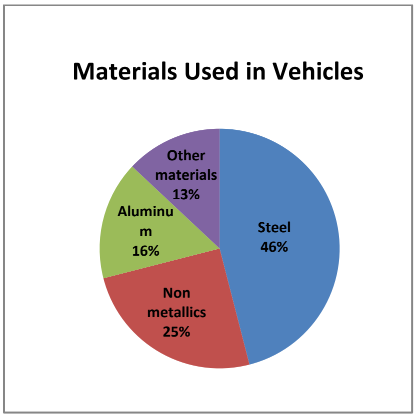
In this study, advanced materials for the aerospace and automotive industries are reviewed, with an emphasis on titanium, aluminium and their alloys. The challenges and opportunities with respect to the SLM of Al-Al_2O_3 nanocomposites are then discussed.

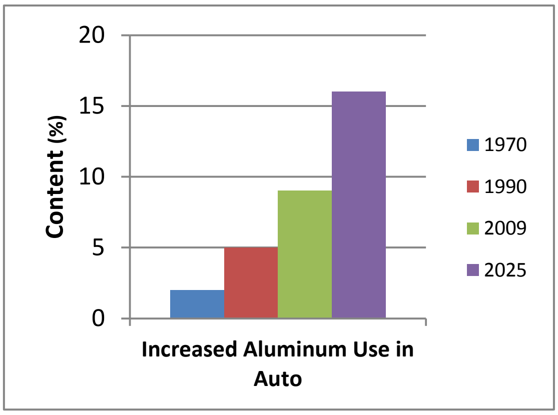
2. Materials for Aerospace and Automotive Industries

Figure 1 [1] illustrates the materials distribution in the Boeing 787 aircraft and modern vehicles. More specifically, Figure 1(a) shows that, in aircrafts, advanced composites account for half the materials used owing to their high specific strength, specific stiffness, fatigue resistance and creep resistance. Aluminium (alloys) also finds wide application in aerospace and accounts for 20% of materials used because of its light weight, high strength-to-weight ratio and good corrosion resistance. In addition, titanium and its alloys are primarily used to manufacture engine parts, comprising 15% of materials used. The balance consists of steel and other materials, at 10% and 5%, respectively. Figures 1(b) and (c) provide information regarding materials distribution and the increased aluminium (alloys) content in vehicles. It is predicted that the aluminium content in vehicles will reach 16% in 2025 compared to 9% in 2009.



(a) Materials in Aircrafts





(b) Materials in Vehicles, 2025

(c) Increased Aluminium Content

Figure 1: Materials Distribution in Aircrafts and Vehicles [1]

Table 1: Mechanical Properties Comparison of Al (alloys) [1]

Type	**Yield strength (MPa)**	**Elongation (%)**	**Fracture toughness, K_{IC} (MPa $m^{1/2}$)**
Al	120	20	
Al-Cu (2224-739)	345	10	53
Al-Zn (7075-T651)	500	10	24(TL), 27(LT)
Al-Li (2099-T83)	520	7.6	27(TL), 30(LT)

Although composites are thought to be the material of choice for airframe structures, their high certification and fabrication costs combined with relatively low resistance to impact have compelled designers to explore and develop alternative materials [1]. Compared to composites, aluminium alloys have been the primary material for aircraft structural parts for more than 80 years owing to their well-known performance, well-established design methods and manufacturing processes, and reliable inspection techniques. In terms of alloying element composition and content, aluminium alloys are classified into nine series, from 1000 to 9000 [8]. Among the aluminium alloys, aluminium-copper (2000 series) alloys are the primary alloys used in airframe structural applications. The addition of magnesium improves strength resulting from the precipitation of the Al_2Cu and Al_2CuMg phases and provides superior damage tolerance and good fatigue crack growth resistance. The Al-Zn alloy (7000 series) is another widely used type of alloy in upper wing skins, stringers and horizontal/vertical stabilizers. 7050-T6 alloys are typically used in aircraft structures due to their high specific strength, machinability and relatively low cost. However, due to their compositions, these alloys are susceptible to corrosion [9].

On the other hand, it is believed that one of the most effective ways to lower the structural weight of aircrafts is by reducing the density of materials. Lithium (density 0.54 g/cm^3) has high solubility in aluminium, which increases the elastic modulus. Another advantage is that aluminium alloys containing Li respond to age hardening [10]. The new generation of 2099 Al-Li alloys have low density, high stiffness, superior damage tolerance, excellent corrosion resistance and weldability for use in aerospace structures that require high strength. It has been suggested that alloy 2099 extrusions could replace 2000 and 7000 series aluminium alloys in applications such as statically and dynamically loaded fuselage structures and lower wing stringers [1]. Table 1 compares the mechanical properties of different typical aluminium alloys.

In the aerospace industry, titanium alloys are used even though titanium is expensive. Compared to aluminium alloys, titanium alloys have a better strength-to-weight ratio, good damage tolerance and excellent corrosion resistance. The better resistance to general corrosion and essential immunity to exfoliation corrosion are the key advantages of Ti alloys over high strength Al alloys. Ti alloys make excellent materials for the cooler portions of aircraft engines, especially in the fan where the stresses on the disk are extremely high. It is essential to use Ti alloys in the fan to minimize the incidence of material defects. In addition to the highly stressed rotors, the fan blades and stages of the compressor air foil are also made from Ti alloys. The evolution of advanced titanium alloys offers even greater potential for their application in aircraft engines. However, this paper has no intention of providing a comprehensive review of this area as several very good review papers have already been published [1, 11].

When temperatures are above 550^{o}C in aircraft engines, Ni base alloys are used instead of Ti alloys. Nickel alloys (Ni melting point 1453^{o}C) have high strength and corrosion resistance at elevated temperatures, which means the rear of the compressor, the combustor and the entire turbine sections are made of Ni base alloys. More details on Ni base alloys have been published in the review paper [11].

In addition to its broad applications in aircrafts, aluminium is also widely used in the modern automotive industry. In vehicles, aluminium and its alloys are used to manufacture various parts, such as the car body, engine blocks, etc, due to their light weight, high strength and good corrosion resistance. However, compared to pure aluminium and various unreinforced aluminium alloys, AMCs provide better mechanical and physical properties, including greater yield strength, improved high temperature properties, wear resistance and a controlled thermal expansion coefficient. Over the past few years, these attributes have found broad application in several demanding fields like the automotive, aerospace, defence, sports, electronics and biomedical industries, as well as for other industrial purposes [2]. For instance, in the automotive industry, AMCs are typically used for pistons, cylinders, brakes and power transfer system elements. Moreover, it is believed that AMCs offer potential as a substitute for monolithic materials, including aluminium alloys, ferrous alloys, titanium alloys and polymer-based composites, in several applications [12].

A wide variety of reinforcement particulates such as Al_2O_3, SiC, TiO_2, B_4C and graphite have been reinforced into AMCs. By comparison to other reinforcements, alumina has shown better thermal stability at high temperatures as undesirable phases are not produced in such materials [13]. Meanwhile, the reinforcement of Al matrix materials with nanosize alumina particles yields superior properties which are significant for engineering requirements. It has been shown that nanostructures have the ability to generate new features and perform new functions and they are thus are more suitable than larger particles and structures. For example, compared to pure Al, 2 vol.% nano-Al_2O_3 additions improve yield strength to around 66%, hardness to around 50% and tensile strength to approximately 80% [14].

3. Challenges in Laser Additive Manufacturing of Al-Al_2O_3 Nanocomposites

One of the additive layer manufacturing (ALM) processes of Al-Al_2O_3 nanocomposites is SLM which is capable of creating three-dimensional metal parts. In this process, 3D-CAD data and high power laser beams function as the digital information and energy source, respectively. The process starts by slicing the 3D-CAD file data into 2D layers and each layer is created by the selective fusing and consolidation of the loose metal powders that are evenly distributed on a plate. The process is repeated layer by layer until the part is complete, which adopts a fully melting mechanism to build parts [15]. Moreover, the main advantages of SLM include higher densification levels, and better surface quality and mechanical properties.

In the laser melting process, laser–material interaction plays an important role which depends strongly on the laser properties, such as power density, wavelength and pulse duration or irradiation time, in addition to the thermophysical properties of the materials (absorptivity, thermal conductivity and density). Normally, the laser–material interaction can be divided into three stages: heating, melting and vaporization. During the first stage, the temperature of the solid is below the melting point. The solid absorbs the energy and the temperature of the material is increased with time. After the solid reaches melting point, the process enters its second stage in which the surface temperature of the liquid is below the saturation temperature. When the highest liquid surface temperature reaches the vaporization temperature of the material, vaporization occurs at the liquid surface and the third stage starts.

Although SLM technology has already been used successfully for several metallic materials in manufacturing, there is little literature regarding aluminium components due to several existing challenges. More specifically, the first challenge in the SLM of aluminium is the high reflectivity (91%) to Nd: YAG laser [4]. Table 2 compares the laser energy absorptance of Al, Fe and Ti [16,17]. In the case of metals, the absorption of laser energy occurs in the very thin layer (one or two atomic diameters) at the surface of the workpiece and the radiation is predominantly absorbed by free electrons. These free electrons are free to oscillate and reradiate without disturbing the solid atomic structure, thus the reflectivity of metals is very high in the waveband and the reflectivity decreases as the wavelength becomes shorter [18]. When a laser scans over the powder bed, the laser energy is directly absorbed by the powder particles. Thus, reducing the aluminium and alumina particle size to a nanoscale has the potential to increase the surface area and absorb more laser energy.

Table 2: Metallic Materials Laser Absorptance Comparison [16, 17]

Material	Absorptance	Laser type
Al	0.09	Nd: YAG laser (λ=1.06 μm)
Fe	0.36	
Ti	0.3	

The second challenge is that SLM depends on being able to spread a thin powder layer which is difficult because aluminium powders are light with poor flowability. In addition, owing to the high thermal conductivity of aluminium, the higher laser powers required to melt aluminium powders are also considered a challenge. However, due to the melting-point depression phenomenon, for laser melting Al-Al_2O_3 nanocomposites, a relatively low laser power is sufficient to melt the powders although the melting point of alumina is 2045^oC. Melting-point depression is the phenomenon of a reduction in the melting point of a material with a reduction in its size. Furthermore, this phenomenon is very prominent in nanoscale materials, which melt at temperatures hundreds of degrees lower than bulk materials. The principle of this phenomenon owes to the fact that nanoscale materials have a much larger surface-to-volume ratio than bulk materials and this therefore alters their thermodynamic and thermal properties.

In addition to the aforementioned challenges, in SLM aluminium components, the most significant problem with respect to the effective melting process of aluminium is oxidation. For example, during sintering, the oxide on the surface of the particles hinders diffusion, while the adherent thin oxide films reduce wettability. As the powder has a surface oxide film that will be incorporated into the molten pool, the oxide film affects the wetting to the surrounding solid parts, and any previously built solid tracks on the side and below the molten pool are also covered by the oxide film [5]. In the laser melting process, wetting implies that the liquid metal spreads on the base metal (substrate or previously sintered layer) instead of balling up on its surface. The phenomena of wetting and spreading are very important for the formation of layers in the SLM process since they determine the spreading behaviour of the melt. Figure 2 shows two different wetting behaviours: poor wetting and good wetting [5]. However, the oxide films are barriers to wetting because their atoms are bonded ionically (ionic bonds). A characteristic of ionic bonds is that there are no free electrons, which is the first condition to form metallic bonds.

Figure 2: (A) Poor Wetting (B) Good Wetting [5]

It has been verified by several researchers that the oxide film on the upper surface of the pool is vaporized under the high temperatures of a laser beam [5, 19]. However, the oxides at the sides of the pool remain intact and the oxides stirred into the molten pool generate regions of weakness and porosity within the part. It is possible therefore that the high laser power needed to process aluminium components is because of the difficulty in disrupting these oxide films rather than a problem in melting the metal [5].

Further, the thin oxide films result in porosity. Generally, the formed pores have two different sources. During the melting stage, the powders melt rapidly and consolidate into a liquid pool. Owing to the high porosity of the powder bed, this liquid pool has a certain amount of interstitial gases which drive out of the liquid. This consolidation of the powder bed is accompanied by a significant density change. If the liquid lifetime is very short, the interstitial gases will remain trapped within the liquid phase and, after solidification, pores can be formed. Another source of porosity, which is considered the predominant factor, is the oxide films stirred into the molten pool in the melting stage. This causes two oxide films to meet, thus forming pores. As it is likely that the formation of oxide films during the SLM process cannot be avoided completely, new methods must be devised to break up these oxide films if the component produced is to be 100% dense [5]. Moreover, it is important that the underlying and surrounding solid partially remelts so that the regions wet and fuse within the molten pool. The mechanisms of porosity formation and the oxide film breaking up are shown in Figure 3.

In the melting stage, in addition to the adherent oxide films on the solid surface, two thin oxide films are formed on the surface and the base of the molten pool. Due to the high temperature in the chamber, it is believed that the oxide film on the top surface of the molten pool is vaporized in the melting stage. Meanwhile, the thin film on the bottom of the molten pool is broken up by Marangoni convection. Marangoni convection is an essential and important part of the mechanism that controls the fluid behaviour of the molten pool. Generally, for a limited range of temperatures above melting point, surface tension increases with increasing temperatures. The effect, called surface-tension-driven convection or Marangoni flow, is a phenomenon whereby the movement of a liquid occurs due to the local difference in the surface tension of the liquid [19]. Surface tension depends on both the temperature and chemical composition at the interface; as the molten pool is maintained under the laser by the addition of powder and the freezing of the solid, it is believed that there is a significant temperature gradient along the molten pool although there is likely to be a smaller difference in the temperature across it, as shown in Figure 3(A).

It has been found that both increasing laser beam power and reducing the beam diameter (i.e. increasing the energy density) makes Marangoni convection stronger and moves the centre of the cells closer to the pool edge [19]. With the vaporization of the oxide film on the top of the molten pool, the surface tension here increases compared to the sides. This, combined with the effects of the temperature profile, will generate stirring in the molten pool that likely breaks up the oxide films on the base but not the sides, as shown in Figure 3(B) [5]. These intact oxide films on both the solid and liquid surfaces form pores where the two thin films meet. Thus, in the future work on SLM Al-Al_2O_3 composites, more attention should be focused on the methods of controlling the oxidation process and disrupting the formed thin oxide films to minimize the porosity level.

4. Opportunities for SLM Advanced Al-Al_2O_3 Nanocomposites

As mentioned previously, in comparison with aluminium and its alloys, AMCs (e.g. Al-Al_2O_3) provide better mechanical and physical properties, such as greater yield strength, improved high temperature properties, wear resistance and a controlled thermal expansion coefficient, and are widely utilized in the automotive, aerospace and defence industries. It has also been found that these nanostructures have the ability to generate new features and perform new functions which are more suitable than larger particles and structures. All these characteristics show the potential of the advanced Al-Al_2O_3 nanocomposites.

The preparation of Al-Al_2O_3 nanocrystalline powders is the first step in the production process and the particle characteristics greatly affect the properties of the final part. By comparison with other processes, high-energy ball milling (HEBM)

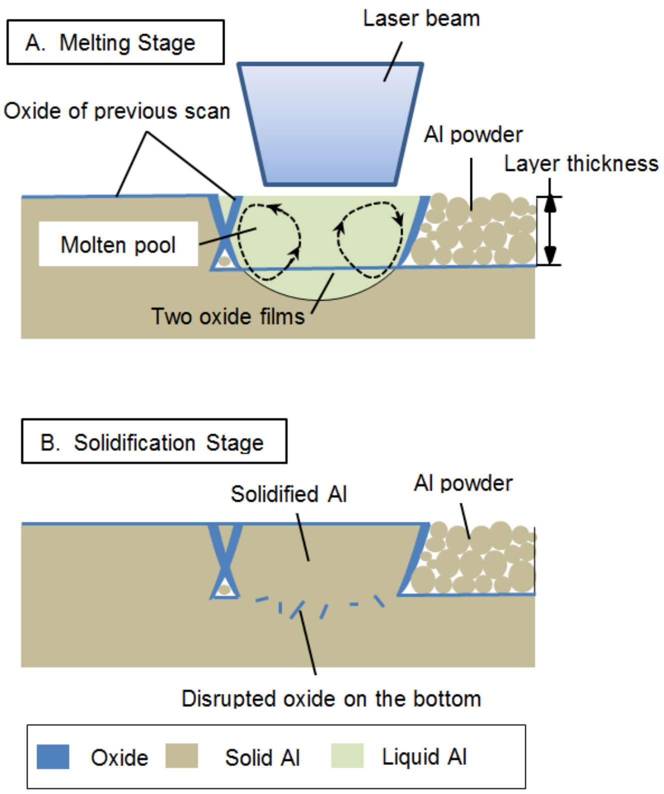


Figure 3: (A) Marangoni Convection in Molten Pool (B) Oxide Disruption and Solidification [5]

has proved to be an effective but simple approach to producing nanocrystalline Al-Al_2O_3 powders and disperse the mixture powders homogeneously. Another advantage of HEBM is its ability to produce bulk quantities of materials in the solid state using simple equipment at room temperature [20, 21]. It is believed that 4 vol.% of Al_2O_3 is the maximum content in the composites as the saturation of the grain boundary with nanoparticulates stops further grain refinement and the extent of agglomeration increases, which reduces the strengthening effect in the nanocomposites [22, 23, 24]. Further research should be focused on the optimization of the process parameters to obtain the finest grains while consuming the least electrical energy.

Due to the layer-by-layer manufacturing mechanism, SLM is capable of producing advanced Al-Al_2O_3 parts with complex geometries. Moreover, SLM is a sustainable manufacturing process as there is no waste in the process and the residual powders can be expected to be recycled if the process parameters are controlled properly. A relative density of 99.8% can be achieved under optimum parameters. It can be foreseen that the future of the SLM of advanced Al-Al_2O_3 nanocomposites is promising given that work is being done on an ongoing basis to resolve the challenges in the process.

5. Conclusions

The metallic materials widely used in the aerospace and automotive industries have been reviewed in this paper in terms of their specific properties. In aircrafts, titanium and its alloys are mainly used for engine parts, while aluminium and its alloys find wide application in airframes and various other supporting structures. In vehicles, thanks to emerging automotive manufacturing technologies, aluminium content is increasing year by year. Meanwhile, due to their superior mechanical and physical properties, advanced Al-Al_2O_3 nanocomposites have been increasingly attracting researchers' attention.

To produce Al-Al_2O_3 nanocrystalline powders, the HEBM process could be an effective but simple approach. Meanwhile, the SLM process can be used to produce advanced Al-Al_2O_3 nanocomposites as it has the potential to create final parts in any complex shapes but without waste. Although there are several challenges in this process, such as high reflectivity, high thermal conductivity and oxidation, the future of the SLM of Al-Al_2O_3 nanocomposites is bright and, once the problems have been resolved, the outcome will be worth the wait.

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References

[1] Dursun, T. and Soutis, C. Recent developments in advanced aircraft aluminium alloys. *Materials and Design*. Vol 56, pp. 862–871 (2014)
[2] Koli, D.K., Agnihotri, G., and Purohit, R. Properties and Characterization of Al-Al2O3 Composites Processed by Casting and Powder Metallurgy Routes (Review). *Int. J. Latest Trends in Engineering and Technology.* Vol 2, pp. 486-496 (2013)
[3] Dadbakhsh, S. and Hao, L. Effect of Al alloys on selective laser melting behaviour and microstructure of in-situ formed particle reinforced composites. *J. Alloys Compd.* Vol 541, pp. 328–334 (2012)
[4] Gu, D.D, Meiners, W., Wissenbach, K. and Poprawe, R. Laser additive manufacturing of metallic components: materials, processes and mechanisms. *International Materials Reviews*. Vol 57, pp. 133–164 (2012)
[5] Louvis, E.,Fox, P., and Sutcliffe, C.J. Selective laser melting of aluminium components. *J. Mater. Process. Technol.* Vol 211, pp. 275–284 (2011)
[6] Olakanmi, E. O. Selective laser sintering/melting (SLS/SLM) of pure Al, Al-Mg and Al-Si powders: Effect of rocessing conditions and powder prperties. *J. Mater. Process. Technol.* Vol 213, pp. 1387–1405 (2013)
[7] Read, N., Wang, W., Essa, K. and Attallah, M. M. Selective laser melting of AlSi10Mg alloy: Process optimisation and mechanical properties development. *Materials & Design*. Vol 65, pp. 417-424 (2015)

[8] Kalpakjian, S. and Schmid, S. R. Manufacturing engineering and technology. *Pearson Education India* (2001)
[9] Necsulescu, D. A. The effects of corrosion on the mechanical properties of aluminium alloys 7075-T6. *UPB Sci Bull*. Vol 73 (2011)
[10] Polmear, I. J. Aluminum alloys - a century of age hardening. *Mater Forum.* Vol 28, pp. 1-14 (2004)
[11] Williams, J.C. and Starke, E. A. Progress in structural materials for aerospace. *Acta Materialia*. Vol 51, pp. 5775–5799 (2003)
[12] Rathod, L. and Purohit, G. K. A study of microstructure and mechanical property of aluminum-alumina metal matrix. *International Journal of Engineering Research & Technology.* Vol 2, pp. 80–85 (2013)
[13] Rahimian, M., Ehsani, N., Parvin, N. and Baharvandi, H. The effect of particle size, sintering temperature and sintering time on the properties of Al-Al_2O_3 composites, made by powder metallurgy. *J. Mater. Process. Technol.* Vol 209, pp. 5387–5393 (2009)
[14] Sajjadi, S. A., Ezatpour, H. R. and Torabi Parizi, M. Comparison of microstructure and mechanical properties of A356 aluminum alloy/Al2O3 composites fabricated by stir and compo-casting processes. *Mater. Des.* Vol 34, pp. 106–111 (2012)
[15] Brandl, E., Heckenberger, U., Holzinger, V., and Buchbinder, D. Additive manufactured AlSi10Mg samples using Selective Laser Melting (SLM): Microstructure, high cycle fatigue, and fracture behavior. *Materials & Design. Vol* 34, pp. 159-169 (2012)
[16] Gray, D. G. American institute of physics handbook. *McGraw-Hill Book Company, 3rd*. (1972)
[17] Fischer, P., Romano, V., Weber, H. P., Karapatis, N. P., Boillat, E., and Glardon, R. Sintering of commercially pure titanium powder with a Nd: YAG laser source. *Acta Materialia*. Vol *51*, pp. 1651-1662 (2003).
[18] Steen, W. M. Laser material processing. 3rd ed., Springer (2003)
[19] Limmaneevichitr, C. and Kou, S. Visualization of Marangoni convection in simulated weld pools. *Welding Journal*. Vol 79, pp.126-135 (2000)
[20] Zhang, D. L. Processing of advanced materials using high-energy mechanical milling. *Progress in Materials Science*. Vol 49, pp. 537–560 (2004)
[21] Suryanarayana, C. Mechanical alloying and milling. *Progress in Materials Science*. Vol 46, pp. 1–184 (2001)
[22] Kang, Y. C. and Chan, S. L. I. Tensile properties of nanometric Al2O3 particulate-reinforced aluminum matrix composites. *Mater. Chem. Phys.* Vol 85, pp. 438–443 (2004)
[23] Poirier, D., Drew, R. A. L., Trudeau, M. L. and Gauvin, R. Fabrication and properties of mechanically milled alumina/aluminum nanocomposites. *Mater. Sci. Eng.* A. Vol 527, pp. 7605–7614 (2010)
[24] Gazawi, A. Microstructure and Mechanical Properties of Aluminium Based Nanocomposites Strengthened with Alumina and Silicon Carbide. Doctor of Philosophy, Materials and Process Engineering, *University of Waikato, Hamilton* (2014)