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Laser Metal Deposition Of Titanium Aluminide Composites: A Review

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Abstract

Development of additive manufacturing (AM) from three dimensional printers with ability of producing parts having no need for tooling continue to wax stronger in the manufacturing field. Laser metal deposition, a technique in AM is usually employed to create solid components from model of computer aided design (CAD). Feeding powder supported by shielding gas employed by this technique, is injected into a melt pool produced by accurately focused laser beam on a substrate. This paper discusses some of the AM technologies available, review on laser metal deposition of titanium aluminide on other metals and alloys, relationship between the processing parameters and structural and mechanical properties of products produced, limitation as regards to the processing parameters employed, applications and possible recommendations.

Selection and/or Peer-review under responsibility of Materials Processing and characterization.

Keywords: Titanium aluminide; composite; additive manufacturing processes; laser metal deposition

1. Introduction

As manufacturing industries continuously face the issue of global competition in the form of high quality, low cost and specialized products demand, additive manufacturing technology with potential to providing the solution continue to gain recognition. Additive manufacturing also refer to as rapid prototyping, three dimensional (3D) printing or freeform fabrication , is a process of forming parts by adding material layer by layer through 3D CAD

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data as against subtractive manufacturing as seen in machining [1,2]. The technique was first developed in 1987 by 3D systems that produced stereolithography apparatus (SLA). Additive manufacturing are basically employed for plastic and metals. The plastic method of additive manufacturing utilizes techniques such as steroelithography apparatus (SLA), selective laser sintering (SLS), fused deposition modelling (FDM), etc. The metal method of additive manufacturing technique include direct metal laser sintering (DMLS), selective laser melting (SLM), electron beam melting (EBM), easyclad, powder bed fusion, lasercusing, laser engineered net shaping (LENS), etc.
The major objective of additive manufacturing is to improve and maintain the performance of fabricated parts by minimizing material usage, production lead time and production cost [3]. The development of 3D printers are slowed down due to the high capital cost, slow processing rate of patent commercialized metal 3D printers and absence of open-source metal alternative [4]. As a result, this makes the major use of the commercialized 3D printer limited to expensive finished products and rapid prototyping. This also makes it almost impossible to use by small laboratories and most small and medium scale companies in the developing world. Herderick [2] noted that only limited number of additive manufacturing technologies are commercially available. Moreover, more needs to be done in concretizing the processes for commercial scale production. Lasers with attribute of rapid heating and cooling provide a control operation as the convection forces in a melt pool created by laser has the ability to increase the diffusion rate, thereby providing a platform for co-fed powder to mix [5]. Laser metal deposition is one of the additive manufacturing techniques that can be employed in the production of solid parts from Computer aided design (CAD) data. In the technique, feeding powder supported by shielding gas is deposited unto a melt pool created by a well-focused laser beam on the substrate [6]. Lorenz et al. [7] mentioned that hybrid manufacturing, an alliance between the computer numerical controlled (CNC) machining and laser-based additive manufacturing are now becoming popular. The hybrid manufacturing technique uses directed energy deposition processes, where powder feedstock is fed into the melt pool produced by a laser. The commercialization of the technology is still at an early stage but possess the ability of delivering not only high deposition rate but also gives products of high accuracy and good surface finish [7]. Titanium was discovered in 1791 by geologist Willam Gregor. Titanium and its alloys have remain very important materials employed in defence, aerospace, autosport, energy, and other manufacturing industries. Titanium among other metals, possess the highest strength-to-weight ratio. This gives designers the opportunity of selecting this material over steel because it is as strong as steel and nearly half the weight of steel [8]. The melting point of titanium up to about 3000□F also makes it useful in naval ships, missiles, spacecraft and armor plating. Part production using titanium material pop-up problems of complexity, waste and lead-time, which make one looks at the rational between the part performance and cost of production. As such, additive manufacturing proffer answers to the problems not only by reducing processing time and cost but also preserve the strength and weight advantages of titanium. Titanium aluminide composites are constantly gaining useful applications in areas like the automotive and aerospace due to the fact that they enhance fuel economy through mass reduction and improved properties such as resistance to oxidation and high temperature performance. The need for the development of sophisticated designs needed for modern vehicles and other machine components, reduction in lead time, reduction in material wastage effect of environmental impact due to manufacturing technique and cost, made additive manufacturing the most preferred option. This paper briefly discusses some of the AM technologies available, review on laser metal deposition of titanium aluminide (metal powder) on other metals and alloys, looking at the relationship between the processing parameters (such as laser scanning speed, power, feed rate etc.), structural and mechanical properties, limitation as regards to the processing parameters employed, applications and possible recommendations.

2. Additive manufacturing processes

Additive manufacturing or layer manufacturing (LM) uses data from 3D model to produce layer by layer near-net-shape parts. The technology has the ability of changing many manufacturing sectors by reducing material wastage, component lead-time and energy usage. The technology also has the ability of ensuring the production of complex components that cannot be produce using conventional processing methods [2]. Additive manufacturing techniques (shown in figure 1) such as three dimensional (3D) welding, laser-engineered net shaping (LENS), shape deposition manufacturing (SDM), three dimensional (3D) micro-welding (3DMW), laser based additive manufacturing (LBAM) and electron beam melting (EBM) with ability of fabricating parts have been developed. The process of obtaining layer by layer metallic parts are referred to as a direct process but when casting process is employed with the pattern produced in layer by layer manner is referred to as an indirect process [9].

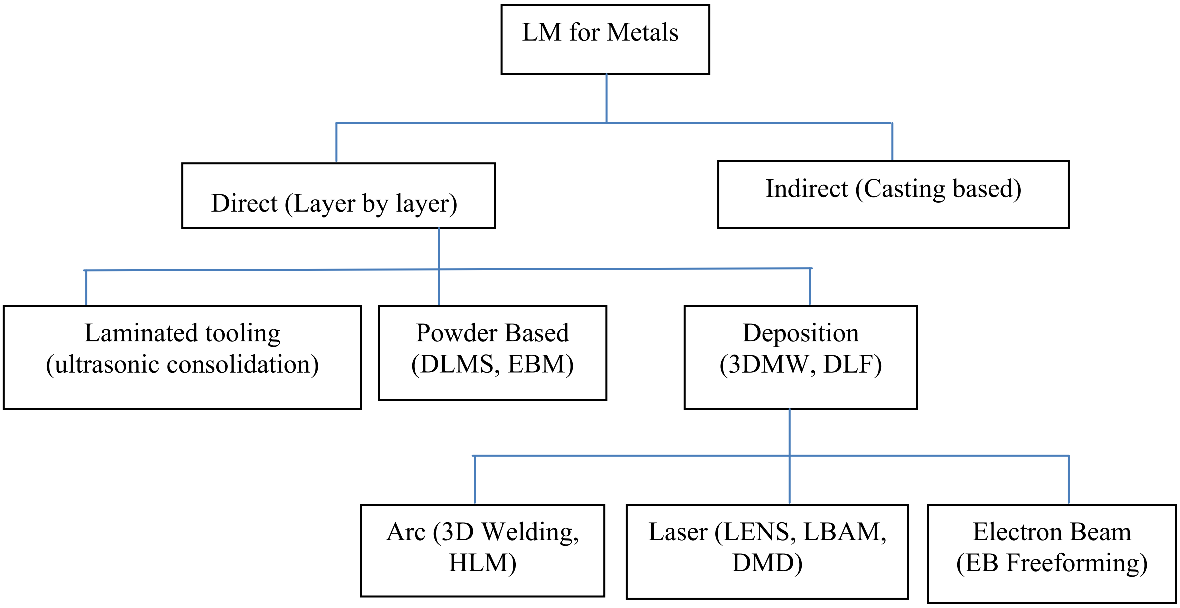

Fig.1. Layer manufacturing techniques for metals [9]

The direct process are divided into laminated tooling (where tooling shape are gotten by cutting and stacking of metal sheet), powder bed (where metallic powder layer is first laid before the required region is then selectively sintered) and deposition technologies where the metallic powder are deposited only on the required area.

2.1 Laser beam melting (LBM) or selective laser melting (SLM)

This is an additive manufacturing process where complex parts through CAD files can be produced directly from metal powder. The principle (as shown in figure 2) involves dividing 3D CAD model into layers and sending to selective laser melting machine. Metallic powder material of grain fraction 10-45µm is then deposited as thin layer on substrate. Geometric data of every layer are transmitted to the powder bed by laser beam. Solid piece layer is produced after the area that should contain the solid material is scanned under inert atmosphere. As the substrate is lowered, the process is repeated until the part is finally produced. The finished part through this process has density that is approximately 100% because standard metallic powders are used. This ensures that parts obtained has similar or better mechanical properties than that of conventional manufactured parts [10]. Bremen et al. [10] noted that different steps are being taking to ensure that the current state of SLM process currently not suitable for series production is developed further.

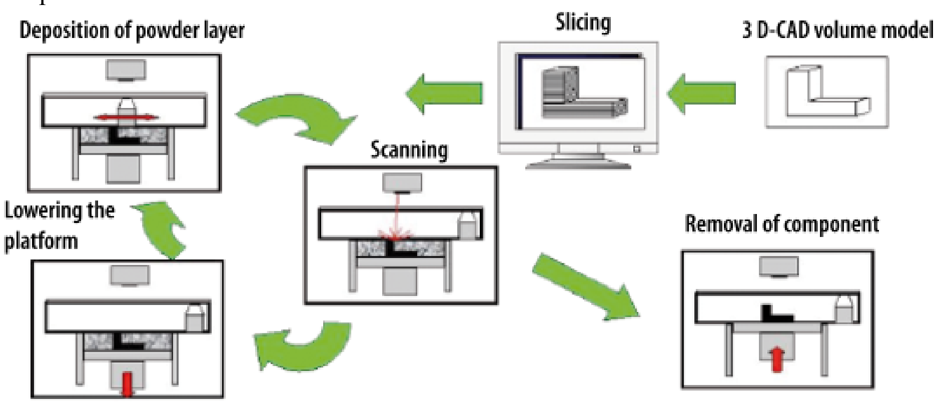

Fig.2. Principle of the SLM process [10]

2.2 Electron beam melting (EBM)

High power electron beam produced the energy required for high productivity and high melting capacity. The process do takes place in vacuum at high temperature. The entire powder bed is heated up by the electron beam for each layer to a desirable temperature. This makes the parts produced through this process practically free of residual stresses and not having martensitic structures in their microstructures.

2.3 3D printing

This is an additive manufacturing process that is seen as a two steps indirect process. Powder layer applied on build platform is agglomerated by a binder fed via printer nozzle. The process is repeated until the parts are produced and because they are still in a green stage, great care is taken for their removal.

2.4 Laser metal deposition (LMD) or direct energy deposition (DED)

The direct energy deposition process utilizes a nozzle that directly deposits melted material on the desired surface where it finally solidifies. The process is very productive than selective laser melting, this is reflected in table 1. The laser metal deposition process is shown in figure 3.

Table 1. Comparison between LMD and SLM [11]

CHARACTERISTICS	LMD	SLM
Materials	• Monolithic • Gradient, hybrid	• Monolithic
Part dimensions	Limited by handling system	Limited by the process chamber (Ø:400mm, height: 500mm)
Part complexity	Limited	Nearly unlimited
Build-up rate	3-140mm^3/s	1-20mm^3/s
Build-up on	• 3D-surface • On existing parts	• Flat surface • Flat preforms

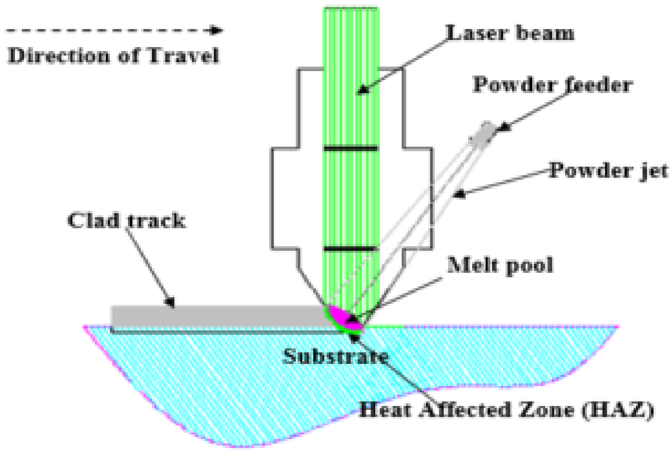

Fig.3. Laser metal deposition process [6]

The advantages of direct energy deposition (DED) process include, repair of parts that seem impossible, excellent metallographic quality, no limit to dimension apart from the machine size, ability to control material deposited, possibility of new topological features, addition of functionality on existing part and less material loss.

3. Additive manufacturing processes for titanium aluminide composite

The unique properties of titanium and its alloys ranging from low weight ratio, high strength and remarkable corrosion resistance have made these materials very useful in numerous places of applications demanding high class of performance reliability such as aerospace, chemical plant, automotive, power generation, medicine and surgery, oil and gas, sports and other manufacturing sectors. These properties and applications make researchers, designers and engineers to continue to research into the development of suitable process to arrive at best grades of titanium alloys that will suit desired applications.

Norsk Titanium [8] makes a breakthrough in the discovering of a process of additive manufacturing. The technique, Rapid Plasma Deposition (RPD) process (as shown in figure 4) is employed in the production of aerospace structures. Layers to near-net-shape requiring little machining are speedily built up by melting titanium wire in an inert argon gas atmosphere.

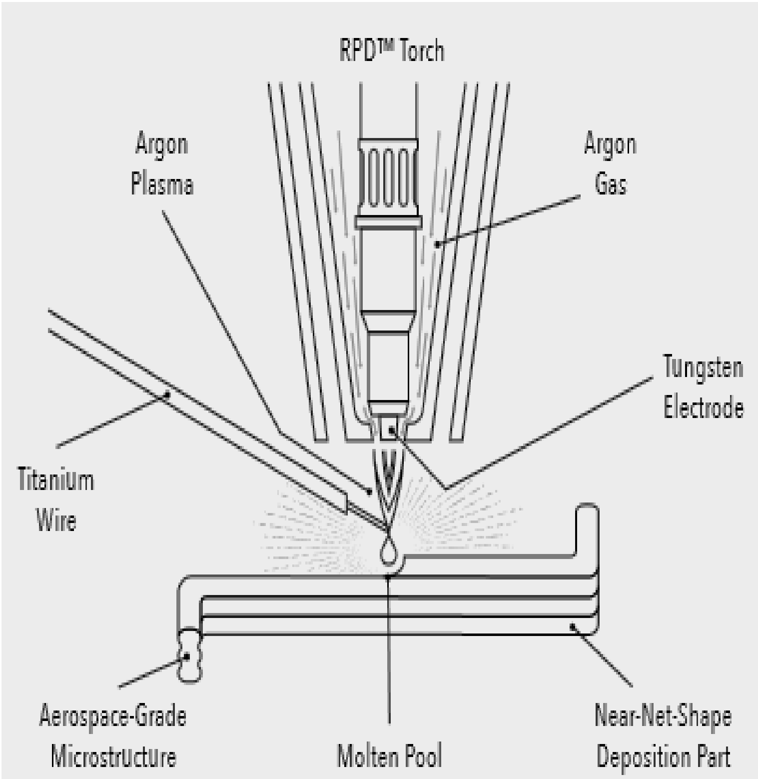

Fig.4. Rapid Plasma Deposition process [8]

Svensson et al. [13] discusses the production of gamma titanium aluminide parts through the electron beam melting (EBM) technique shown in figure 5. Electron beam power of 3KW and metallic powder size between 45-105µm (-140/+325 mesh) are typically employed in this process. The technique can be applied in the medical implants, aerospace, automotive etc. Gamma titanium aluminide is a suitable material in in structural aerospace applications. The advantages of the EBM process include production of parts with small level of internal defects, achievable homogenous microstructure, fine grain size, absent of residual stresses as a result of high processing temperature and low material wastage.

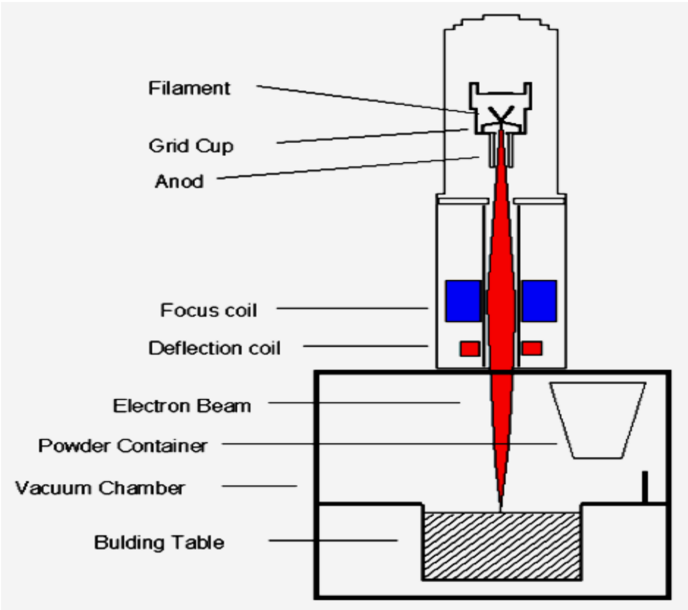

Fig.5. Electron beam melting process [13]

A non-powder based technique called ion fusion formation (IFF) was developed by Honeywell Aerospace [2]. The technique is utilizes wire feedstock on arc-based welding torch in depositing metal as an inert gas acts as a plasma forming gas. Direct metal depositions were electronic interface controllable positioning table is employed in parts production. The technique has been employed in depositing metals and alloys such as 374 stainless steel, aluminium and Ti6Al4V. The advantage of the technique is seen in it fast build-up speed and production of fully dense deposited parts that do not need hot isostatic press post treatment. This technique has its own limitations such as the machining of the produced part surface and precision not as accurate as it should be when lower deposition rate is required.

In the studies of Tang et al. [14], high niobium-containing Ti-45Al-7Nb-0.3W titanium aluminide alloy was studied using selective electron beam melting. The investigation was based on the microstructural defects usually caused by aluminum vaporization. Higher preheating temperatures and reheating every solidified layer (intermediate reheating process) was employed in order to prevent macro and micro-cracks. The actions effectively freed the thermal stresses created during the selective electron beam melting process, thereby preventing cracks formation. The alloy produced through the process edited unique properties and the it was recommended that with right processing parameters and pathways, high performance titanium aluminide alloys can be produce using the selective electron beam melting process and noted that producing pore-free microstructure of the alloys using this process still remain a challenge.

Ma et al. [15] used the approach of in-situ alloying using separate feeding of commercially available pure titanium and aluminium wires into a weld pool with heat source from gas tungsten arc welding to fabricate gamma-titanium aluminide alloy components. Microstructure and mechanical properties of the fabricated titanium aluminide material and influenced on its location within the fabricated component was examined. Tensile test and microhardness measurements results showed proportionally homogenous mechanical characteristics all over the deposited material while the near substrate region close to the pure titanium substrate showed exception to the homogeneity due to the fact that alloying process was not properly controlled at that region. The results from strengthening mechanisms and microstructure variation of the manufacturing method indicate that full density titanium aluminide parts can be produced using the technique.

In the work of Gasper et al. [16] three different methods using direct metal deposition process for in-situ synthesis of titanium aluminide where examined. Among the methods employed was a process of powder preparation in additive manufacturing referred to as satelliting, where smaller powder fraction is used to coat larger parent powder. In this case, fine TiO_2 was used to satellite aluminium parent particles to form particulates of Al_2O_3 intermetallic matrix composite. The second method used a combination of wire and single powder feeding where titanium wire and aluminium powder was used to form Ti-50Al. The last method uses loose mixed powders and wire to form Ti-48Al-2Cr-2Nb alloy. Wire and powder simultaneous delivery in the process is done to eliminate problems faced when using only wire or powder feedstocks. To be able to compare the three methods based on the effect of processing parameters on the deposits formed, optical microscope, scanning electron microscope and electron diffraction X-ray where used to characterized. $TiAl_3$ matrix placed with Al_2O_3 particulates intermetallic matrix composites are fabricated at smaller energy densities with the three feedstock methods efficiently producing titanium aluminides in-situ with differs outcome in terms of composition, microstructures formed and quality of the track deposits.

4. Laser metal deposition of titanium aluminide composite

Titanium aluminide alloys are intermetallic compound that falls in the group of high temperature structural materials with exemplary properties that makes them applicable in various manufacturing fields [17]. Ti-6Al-4V an alloy of titanium are expensive but remains the most sort titanium alloy which makes the need of reducing waste of the material a paramount concern and as such makes rapid prototyping a suitable option of utilizing the material for parts production [18]. The advantages associated with the composite make researchers and users of engineering materials to continue to seek for an optimum way of producing parts using certain techniques. This made laser metal deposition technique one of the viable technique employed in the production of composite materials.

In the research carried out by Tlotleng et al. [5], effect of laser power on microstructure, hardness and composition of the produced TiAl coatings was studies. The fabrication of TiAl coatings was done through direct laser metal deposition process. Keeping laser scanning speed constant and varying laser power, Ti and Al powders from different hoppers where injected at the same time. Ti and Al powders Laser power 1.0, 1.3 and 1.5KW gives a lamellar structure while a refined dendritic structure was observed at 2.0KW. The result obtained also showed that the coatings contain $TiAl_3$ and $TiAl_5$ with stable phases at high temperature processes. Finally, hardness evaluation revealed that the coatings produced are that of $TiAl/TiAl_3$ based.

Cárcel et al. [19] carried out a study on the deposition of TiAl intermetallic coating on Ti6Al4V substrate employing the laser cladding technique. Process parameters such as the scanning speed, laser power, preheating temperature and feeding rate were optimized. Using optical microscope and scanning electron microscope, characterization of microstructure of the coating was performed. It was noted that the cooling rate definitely affects the hardness of the material and cracking of coatings and tracks. The research also revealed that increase in cooling rate will lead to an increase in hardness and cracking. It was however noted concluded that previously heating and during process reheating will improve the cracking result that pose a major defect in the cladding processing of TiAl.

In the work of Zhang et al. [20] outcomes on microstructural characterization of titanium aluminide intermetallics fabricated with laser engineered net-shaping (LENS) method were highlighted. This is not only to improve the understanding of likely microstructural and mechanical properties of deposited material obtainable using the LENS method but also to compare the microstructures gotten through the LENS technique to that of the conventional processing method. It was however noted that operation parameters have a great outcome on deposited material microstructure. Explaining that based on the substrate material and the laser beam Z-axis positioning, gamma or equiaxed metastable α_2-Ti_3Al microstructure is obtainable for titanium aluminide alloys. The post heat treatment carried out for 15min. at 900□C on the metastable α_2 microstructure results in the creation of α_2-Ti_3Al (in high percentage volume) and gamma titanium aluminide. It was finally concluded that the microstructure formed is anticipated to enhance the tensile strength greatly.

Srivastava et al. [21] using Ti-48Al-2Mn-2Nb atomized powder as material feedstock, fabricates TiAl alloy material. Effects caused by processing parameters (like scan rate, powder size, powder feed rate, laser power and Z-increament) on features like micro and macrostructure, build width and height were studied. Using a high feedback mechanism to monitor and correct processing parameters, range of processing parameters in fabricating component at constant build rate were established. Srivastava et al. [22] in another study, using the same powder material characterized the microstructures of samples produced from the same direct laser fabrication (DLF) process. With the characterization taking place both after the laser fabrication process and after heat treatments using optical microscope, scanning electron microscope and transmission electron microscope. In controlling the microstructural morphology, laser power and scanning speed process parameters were employed. The study revealed fine inhomogeneous microstructure as compared to process material from the conventional method. At 973K laser treated microstructure was stable with coarse grain beginning to be visible at 1273K. After annealing at a temperature of 1073K for 24 hours, complete uniform recrystallized microstructure was achieved.

Mahamood et al. [23] worked on the effect of laser power on microstructure and microhardness material formed from Ti6Al4V powder deposited on Ti6Al4V substrate through laser metal deposition technique. Keeping the values of scanning speed at 0.005m/s, powder flow rate at 1.44g/min and gas flow rare at 4l/min, laser power 0.8 – 3.0Kw was used to deposit tracks of Ti6Al4V powder on the substrate. Using optical microscope and Vickers hardness tester, microstructure and microhardness of deposited samples were studied. Layer bands as a result of re-melting of previous layers by preceding layers were observed in all samples. It was also discussed that the shrinkage process taking place in the fusion zone due to interaction of deposited melt pool formed by the substrate might also be responsible for the creation of the layer band. It was concluded that increasing the laser power will lead to increase in microhardness and the decrease in the density of columnar prior β-grain structure.

5. Research direction in laser metal deposition of titanium aluminide composite

Research breakthroughs in the development of composites with unique properties and numerous advantages associated with laser metal deposition technique do not mean that there are no limitations. The limited number of the commercially available technology, additive manufacturing laboratories and scarcity of some metal powder are some of the challenges limiting research in this area. Also the uneven deposition of powder, defect of cracking usually associated with this technique and optimization of processing parameters are areas that need to be looked at in the areas of development of composites. Other areas where the composites will also be useful should also be investigated.

6. Summary

There are several additive manufacturing technologies available in the production of metal composites. Using different feedstocks, some of the techniques that have been employed in production of titanium aluminide composites include the arc technique, lasers and electron beam. These techniques have been used in the production of parts that ordinarily could not be produced using traditional machining technique. Additive manufacturing technique (laser metal deposition) has successfully been applied in fields such as the aerospace, surgery, medicine, automotive etc. The high productivity of the laser metal deposition over other additive manufacturing technique such as selective laser melting makes it highly useful in production of parts. Other advantages of the process include the repair of parts that seem impossible, excellent metallographic quality, no limit to dimension apart from the machine size, ability of controlling material deposited, addition of functionality on existing part and less material loss. However, the technique sometimes exhibits some limitations usually seen as cracks and uneven deposition of metal powder on substrate. Recommendations on issue of crack defect minimization and elimination are through preheating and during process heating. Great relationship exist between the processing parameters (such as laser power, laser scanning speed and the powder flow rate), structural and mechanical properties of products produced using the technique. The right applications of processing parameters have always led to the development of titanium aluminide composites with excellent mechanical and structural properties.

References

[1] M. Aliakbari, "Additive Manufacturing : State-of-the-Art , Capabilities , and Sample Applications with Cost Analysis," *KTH*, 2012.

[2] E. Herderick, "Additive Manufacturing of Metals : A Review," *Mater. Sci. Technol.*, no. 176252, pp. 1413–1425, 2011.

[3] P. A. Kobryn, N. R. Ontko, L. P. Perkins, and J. S. Tiley, "Additive Manufacturing of Aerospace Alloys for Aircraft Structures," in *Meeting Proceedings RTO-AVT-139*, 2006, pp. 3-1-3–14.

[4] G. C. Anzalone, C. Zhang, B. A. S. Wijnen, P. G. Sanders, and J. M. Pearce, "A Low-Cost Open-Source Metal 3-D Printer," *IEEE Access*, pp. 803–810, 2013.

[5] M. Tlotleng, B. Masina, and S. Pityana, "Characteristics of laser In-situ alloyed titanium aluminides coatings," *Procedia Manuf.*, vol. 7, pp. 39–45, 2016.

[6] E. T. Akinlabi and S. A. Akinlabi, "Powder Flow Rate Influence on Laser Metal Deposited TiC on Ti-6Al-4V," no. Lmd, 2016.

[7] K. A. Lorenz, J. B. Jones, D. I. Wimpenny, and M. R. Jackson, "A REVIEW OF HYBRID MANUFACTURING," in *Solid Freeform Fabrication Conference Proceedings (Vol. 53)*, 2015, pp. 96–108.
[8] Norsk Titanium, "The dawn of a new industry: Rapid plasma deposition ^{TM}," *Modem Metals*, 2016.
[9] K. P. Karunakaran, S. Suryakumar, V. Pushpa, and S. Akula, "Low cost integration of additive and subtractive processes for hybrid layered manufacturing," *Robot. Comput. Integr. Manuf.*, vol. 26, no. 5, pp. 490–499, 2010.
[10] S. Bremen, W. Meiners, and A. Diatlov, "Selective Laser Melting A manufacturing technology for the future ?," *Laser Tech. J.*, no. April 2012, 2012.
[11] A. Weisheit and G. Rolink, "Influence of Process Conditions in Laser Additive Manufacturing on the Microstructure Evolution of Fe-Al Alloys- A Comparison of Laser Metal Deposition and Selective Laser Melting .pdf," in *AAM Workshop, MPEI*, 2016.
[12] E. T. Akinlabi and S. A. Akinlabi, "Advanced Coating : Laser Metal Deposition of Aluminium Powder on Titanium Substrate," in *Proceedings of the World Congress on Engineering*, 2016, vol. II.
[13] M. Svensson *et al.*, "Additive Manufacturing of Gamma Titanium Aluminide Parts by Electron Beam Melting (EBM ®)," in *Titanium 2010*, 2010.
[14] H. P. Tang, G. Y. Yang, W. P. Jia, W. W. He, S. L. Lu, and M. Qian, "Additive manufacturing of a high niobium-containing titaniu aluminide alloy by selective electron beam melting," *Mater. Sci. Eng. A*, vol. 636, pp. 103–107, 2015.
[15] Y. Ma, D. Cuiuri, C. Shen, H. Li, and Z. Pan, "Effect of interpass temperature on in-situ alloying and additive manufacturing of titanium aluminides usinf gas tungsten arc welding," *Addit. Manuf.*, vol. 8, pp. 71–77, 2015.
[16] A. N. D. Gasper, S. Catchpole-Smith, and A. T. Clare, "In-situ synthesis of titanium aluminides by direct metal deposition," *J. Mater. Process. Technol.*, vol. 239, pp. 230–239, 2017.
[17] J. Lapin, "TiAl-BASED ALLOYS : PRESENT STATUS AND FUTURE," *Hradec nad Moravici*, pp. 1–12, 2009.
[18] D. Yvonni-Effrosyni, "Direct Laser Metal Deposition- [DLMD] of Titanium Matrix Composites : Analysis of Microstructure and Mechanical," National Technical University of Athens, 2014.
[19] B. Cárcel, A. Serrano, J. Zambrano, V. Amigó, and A. C. Cárcel, "Laser cladding of TiAl intermetallic alloy on Ti6Al4V . Process optimization and properties .," *Phys. Procedia*, vol. 56, pp. 284–293, 2014.
[20] X. D. Zhang *et al.*, "CHARACTERIZATION OF LASER-DEPOSITED TiAl ALLOYS," *Scr. Mater.*, vol. 44, pp. 2419–2424, 2001.
[21] D. U. Srivastava, I. T. H. Chang, and M. H. Loretto, "The optimisation of processing parameters and characterisation of microstructure of direct laser fabricated TiAl alloy components," *Mater. Des.*, vol. 21, pp. 425–433, 2000.
[22] D. Srivastava, I. T. H. Chang, and M. H. Loretto, "The effect of process parameters and heat treatment on the microstructure of direct laser fabricated TiAl alloy samples," *Intermetallics*, vol. 9, pp. 1003–1013, 2001.
[23] R. M. Mahamood, E. T. Akinlabi, M. Shukla, and S. Pityana, "Laser Metal Deposition of Ti6Al4V : A Study on the Effect of Laser Power on Microstructure and Microhardness," in *Proceedings of the International MultiConference of Engineers and Computer Scientists*, 2013, vol. II.