Chapter

Laser Based Additive Manufacturing Technology for Fabrication of Titanium Aluminide-Based Composites in Aerospace Component Applications

Sadiq Abiola Raji, Abimbola Patricia Idowu Popoola, Sisa Leslie Pityana, Olawale Muhmmed Popoola, Fatai Olufemi Aramide, Monnamme Tlotleng and Nana Kwamina Kum Arthur

Abstract

Titanium aluminides has the potential of replacing nickel-based superalloys in the aerospace industries because its density is almost half that of nickel-based alloys. Nevertheless, the room temperature properties (ductility) have made the wider application of this class of intermetallic alloy far from being realized. This has led to various research been carried out in adjusting the production processing and/or material through alloying, heat treatment, ingot metallurgy, powder metallurgy and most recently additive manufacturing processing. One of the additive manufacturing processing of titanium aluminide is laser engineered net shaping (LENS). It is used to produce components from powders by melting and forming on a substrate based on a computer-aided design (CAD) to shape the components. This contribution will focus on the laser processing of titanium aluminides components for aerospace applications. Also, the challenges confronting this processing techniques as well as suggested finding to solve the problems would be outlined. The objective of this work is to present an insight into how titanium aluminides components have been developed by researchers with emphasis on aerospace applications.

Keywords: additive manufacturing, titanium aluminide, composites, laser additive manufacturing (LAM), aerospace components

1. Introduction

Aerospace engine components are exposed to high temperatures as a result of enormous heat generation in the engine and formation of large temperature rise across the structural parts. These components are generally expected to possess a high strength-to-weight ratio in order to give high thrust, improved fuel efficiency at minimal fuel consumption while increasing speed of flight. Aircraft engines are usually fabricated by titanium alloys, nickel-based super alloys, superior steels or ultrahigh-temperature ceramics. Moreover, an important engineering material for manufacturing of gas turbine and aircraft engine components are alloys of titanium (Ti) because of good properties like corrosion resistance, excellent specific strength and most especially their low density [1]. Also, due to the biocompatibility of these alloys, they have been applied in biomedical industries as implants [2–4] and prosthetic beak [5]. The poor wear performance and low hardness of titanium alloys constrained their adoption in fabricating components to be subjected in contact forces of friction and wear [3, 6]. Likewise, titanium alloys have not been impressive for load-bearing components (LBC) in the aerospace industry because of uneven stress distribution on parts [7].

Beta titanium (β-Ti) alloys is reported to have been used to fabricate landing gears in Boeing aircraft from the Ti-5Al-5Mo-5V-3Cr because of better strength-toughness mishmash in β-Ti alloys compared to α + β and α alloys [8]. Titanium intermetallic alloys have great potentials in aerospace, automotive and power plants especially titanium aluminides (TiAl) because of their excellent creep and light-weight in relation to nickel-based superalloys [9]. The most feasible TiAl alloys with engineering interest are those of 44–48 at.% Al content because of the eutectoid transformation reaction occurring during solidification and cooling process [10]. **Figure 1** displays the phase diagram of Ti-Al between 0 and 60 at. % aluminum. Titanium matrix composites (TMCs) reinforced with ceramics has increased due to improvement in heavy load-bearing, wear and friction performance in service due to material efficiency with lower cost of parts fabrication.

A possible replacement of Ni-based superalloys is gamma-titanium aluminide (γ-TiAl) considered in manufacturing aero-engine and automobile engine parts because of their high strength, high stiffness, light weight good oxidation and corrosion resistance [11–20]. The choice of γ-TiAl is hinged on the fact that its density is almost half of Ni-based superalloy and high temperature creep properties [21, 22] with application temperature up to 750°C [23]. These has made γ-TiAl to be favorably accepted in aerospace industry. However, aero engine component like turbocharger operate at temperatures between 700 and 950°C which presents a concern of oxidation reaction apart from its room temperature ductility [22]. γ-TiAl

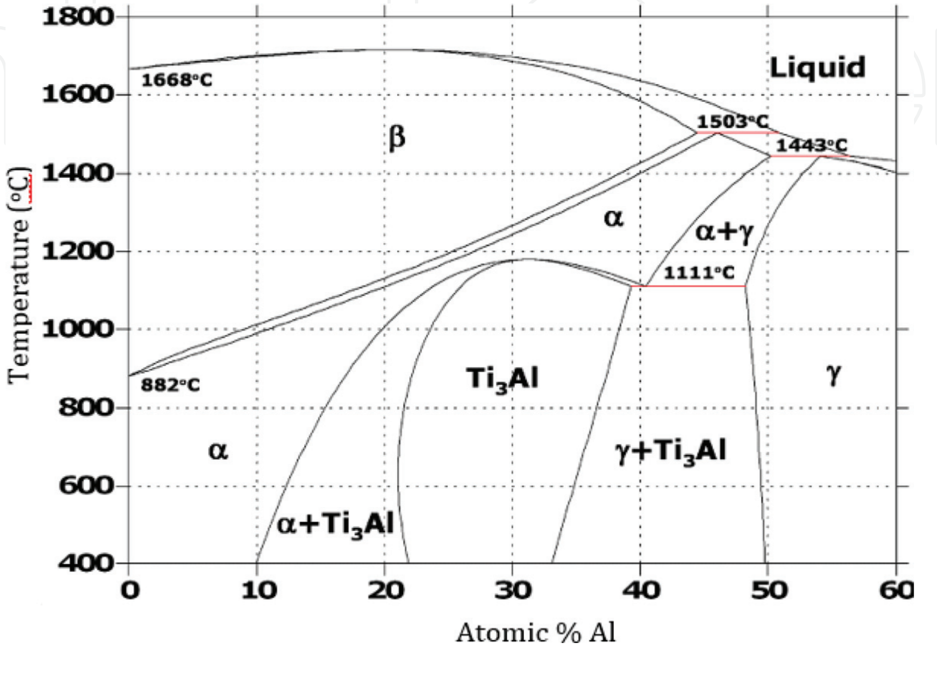

Figure 1.
Ti-Al binary phase diagram.

of 48 at.% Al generally comprise of a γ-phase and α_2-phase with $L1_o$ and DO_{19} structure respectively (major: γ-TiAl, minor: α_2-Ti_3Al) typically referred to as γ-TiAl [10, 24]. This γ-TiAl-based alloy are continuously been improved upon in the manufacturing nozzles, low pressure turbine blade (LPTB) and turbochargers in aerospace engines [25].

General Electric has applied the Ti48Al2Cr2Nb alloy called the GE4822 to manufacture the Boeing-787 Dreamliner's engine known as GEnx-1B that reduces both fuel consumption and CO_2 emission by 15% [11, 21, 26]. Due to the GE4822 alloys high-temperature capability, there has been works on improving the ductile property of γ-TiAl which have been used for low-pressure turbine (LPT) blades [11, 16, 18, 27] and to expand the temperature range 800–850°C [11]. High Nb-containing TiAl known as TNM have been produced with higher yield strength, oxidation resistance and better creep than conventional TiAls [15, 19, 23, 26, 28, 29].

However, the extremely poor tensile ductility (<1% elongation) of TiAl-based alloys at room temperature, poor fracture toughness and high-temperature poor workability makes it difficult to fabricate and strongly limits their applications in the industry [10, 13, 15, 16, 18, 30]. This has made conventional processing techniques very problematic in manufacturing TiAl-based components. Hence, a lot of interest in improving the ambient temperature characteristics and oxidation resistance at elevated temperature, methods such as alloying and post-processing heat treatment has been suggested to help advance its properties.

Apart from the potentially improved geometrical complexity, additive manufacturing (AM) permits manufacturing of innovative materials with functionally graded capabilities during fabrication [14]. The applicability of TiAl alloys is becoming more progressive due to the growing knowledge of the connections concerning mechanical properties and microstructural evolution as well as modifications in processing operations [18]. However, even with AM technologies issues of the mass production quantities is still not making the technique cost-effective [31].

Currently, AM has gained acceptance for manufacturing customized products with complex geometrical freedom, more homogeneous microstructure and functionally enhanced parts gradually replacing traditional processes [14, 28, 32]. Due to this property, it is possible to manufacture components and finished parts which could not be implemented with conventional manufacturing technologies or only at great expense. AM routes is poised to produced γ-TiAl parts for aerospace applications.

Laser additive manufacturing (LAM) is a class of AM process that makes use of high-powered laser beam in melting and fabricating metal powders into three-dimensional (3D) components from a predesigned computer-aided design (CAD) model. One of the highly desirable LAM techniques is laser engineered net shaping (LENS®) regarded for producing ceramics, composites and functionally graded materials (FGMs) which are difficult to produce [33, 34].

The objective of this work is to give an overview of LAM of TiAl alloys and composites while presenting a review of crucial matters, investigation tendencies, fabrication and progress achieve on γ-TiAl based materials for aerospace. A succinct overview of TiAl was first presented followed by AM of titanium alloys particularly those applied in aerospace industries. The paper subsequently highlights a comprehensive appraisal of latest studies on γ-TiAl laser processing and post-processing effects on microstructural evolution and mechanical properties. Prospects, challenges and suggested findings were discussed at the end of this work.

2. Additive manufacturing (AM)

AM is a material joining process from a three-dimensional (3D) CAD model data to build an object, in typically layer by layer [32, 35]. AM has been known by names which includes freeform fabrication (FFF), additive layer manufacturing (ALM), rapid prototyping (RP) and 3D-printing (3DP). AM have been widely adopted in industries especially the aerospace and medical field with recent application in radio-frequency (RF) for microwave and millimeter wave devices [32]. The distinguishing feature of this technology is ability to manufacture objects through layer upon layer building [36] and consistent component functions requiring little or no additional process [37].

The two key classes of AM technologies are direct energy deposition (DED) and powder bed fusion (PBF) as depicted in **Table 1**. The DED methods offers prospects in engineering applications for producing functional parts with intricate geometries from metallic powders [31]. The powder particles used are preferably spherical with the DED being more sensitive in size distribution and wires are adopted as precursor for certain DED processes for higher production rate [38]. The process melts the material feedstock (powder or wire) using a high-powered laser beam. The most commonly used lasers are CO_2 and ND: YAG which has been used for fabricating complex and customized parts, prototyping of metallic parts and repairing/cladding of components [31]. This method is ideal to directly make components with limited tooling but the produced parts exhibits relatively low fracture toughness and prone to defects like cracks and pores due to fast heating and cooling rates involved [39, 40].

In the PBF techniques, a heating source (laser or electron beam) scans metallic powders on a preplaced build platform to melt the powders in a predefined path. This is controlled based on CAD model to build the object in a layer by layer tool path. It has the benefits of reduced lead time and material waste [41] and control of melt pool dynamics and stability [42].

There have been remarkable improvements in AM primarily by the Ti alloys production for aerospace components. Though, PBF is competent to make near-net shaped objects and DED also can be applied to refurbish/repair parts and modify features apart from fabricating 3D objects. The high-temperature gradient due to focused instant heating and cooling is the main difficulty encountered by these techniques.

The majority of investigations on AM materials demonstrates that their mechanical properties of better than the traditionally manufactured titanium alloys. The principal application of additive manufactured Ti-alloy is the aerospace

Classes	Technology	Source of energy	Material used
Powder bed fusion (PBF)	Electron beam melting (EBM)	Electron beam, laser beam	Metal, ceramics and polymers
	Selective laser melting (SLM)		
	Direct metal laser sintering (DMLS)		
	Selective laser sintering (SLS)		
Directed energy deposition (DED)	Laser engineered net shaping (LENS)	Laser beam	Metals (powder and wire)
	Laser cladding		
	Electronic beam welding (EBW)		

Table 1.
The major classes of additive manufacturing (AM).

industry followed by the medical industry while its gradually been accepted in automotive industry. AM presents encouraging platform to produce highly effective Ti-alloy component with intricate geometry [43, 44]. Whereas, these alloys are continuously been studied, the problem encountered is due to their additional processing requirements.

Laser-based AM, however, achieves the built parts defined in a CAD model by melting and solidifying powder on a layer by layer basis [45]. This method is known to have been adopted in aerospace to manufacture and create components of graded material using Ti-based alloys. The LAM technologies produce fully dense parts from wire or powder feedstock [46, 47]. It has the merit of cost and time saving in comparison to traditional methods of casting and forging. A pertinent problem encountered in LAM when processing titanium matrix composites form various literatures is the unevenness of particle distribution. Also, the appearance of non-melted particles leading to reduced plasticity.

2.1 Additive manufacturing of titanium alloys

One of the titanium alloys that are ideal for aerospace applications is the β-Ti alloy because it has a combined property of high strength and lightweight [48]. Titanium alloys have proven to be extremely attractive and important materials in aerospace applications because of excellent combinations of outstanding corrosion and mechanical properties [39, 47, 49, 50]. Recently, there has been increased interests in the development of additively manufactured titanium (and their alloys) parts in industries. However, the widespread applications are mitigated by expensive processing involved compared to some material of similar function [39].

A lot of studies have shown that Ti-alloys produced by AM possess considerable better mechanical properties than the conventional materials. Also, recent development has led to increased acceptance of the technologies, contributing new potential concerning functional incorporation and lightweight components.

Saboori et al. [31] presented a review of AM on titanium components by direct laser deposition (DLD) analyzing the significance prospects of DED process. The connection among titanium alloys microstructural characteristics and process parameters were outlined. It was understood that DED processed parts undergo complex thermal history severely induced due to process uncertainties and process parameters. Even with attempts in optimizing process parameters to curtail flaws, enhance mechanical properties and microstructure of the component, there still existed the challenge of striking a balance. However, titanium parts fabricated by DED still had increased strength and poor ductile properties. It was stated that this alloy suffer anisotropy in the tensile characteristics because components fabricated horizontally demonstrate increased ductile strength compared with those build vertically.

In the work of Hu et al. [3], titanium matrix composites (TMC) has been fabricated by LENS using a 3D quasi continuous network (3DQCN) and TiB as reinforcement. The author examined the influence of energy input and reinforcement on parts quality and wear resistance. Superior wear performance was recorded as a result of TiB addition as a reinforcement. In a related work by Hu et al. [6], the author examined the influence of laser power and TiB reinforcement on mechanical properties. It was shown that laser power greatly affects the resulting microstructures but the strengthening of TiB increases the ultimate compressive strength (UCS) and microhardness of TiB-TMCs. **Table 2** shows influence of laser power in varying microhardness of LENS processed TiB-TMCs.

Also, the mechanical properties and defects (porosity) of TiB-TMCs parts fabricated using an innovative ultrasonic vibration-assisted (UV-A) LENS have been

Materials	Laser power	Microhardness ($HV_{1.0}$)	Processing
Cp-Ti	200 W	345.5 ± 5.4 [3]	LENS
Cp-Ti	125 W	304 ± 10 [6]	LENS
TiB-TMCs	200 W	392.6 ± 8.9 [3]	LENS
TiB-TMCs	125 W	339 ± 9 [6]	LENS
TiB-TMCs	200 W	393 ± 9 [6]	LENS
TiB-TMCs	200 W	405–429 [52]	UV-A LENS
TiB-TMCs	300 W	428–488 [52]	UV-A LENS

Table 2.
Microhardness comparison of TiB-TMCs.

investigated by Ning, Hu and Cong [51]. The procedure adopted exhibited remarkable influences on porosity, pore size, TiB whisker size and distribution, QCN microstructural grain size and microhardness. Consequently, fine microstructures were obtained due to refinements of both TiB whiskers and QCN microstructural grains UV-A LENS providing larger area of grain boundaries to hinder the dislocation motion, thus improving the microhardness of fabricated parts.

A research was conducted by Grove et al. [50] to investigate and compare the surface integrity and machinability of Ti-5553 alloy with composition Ti-5Al-5V-5Mo-3Cr produced by casting, SLM and SLM + heat treatment (in-situ). Higher tool wear was noticed in the in-situ heat treated alloy while the tool wear for the other two does not seem to differ. Therefore, it proves titanium alloys' machinability is extremely affected further processing methods.

According to Uhlmann et al. [52], the aviation industry requires a drastic reduction in NOx and CO_2 emission in the coming years ahead. The authors' study was focused on highly effective and efficient titanium alloys with optimizing process parameters for structures manufactured by the SLM machine. The post-processing of TiAl6V4 parts fabricated by SLM display vast possibility of enhancing surface quality. Examination of computed tomography and microstructure confirms that porosity of titanium alloy parts can be minimized through HIP-process.

Silica ($SiCO_2$) coatings have been created on commercially-pure titanium (Cp-Ti) by Heer and Bandyopadhyay [53] using LENS with subsequent stress relieve heat treatments and post-deposition laser passes. Ti_5Si_3 phase was formed leading to high hardness of ~1500 HV in the coatings and wear rate was mostly reduced in comparison to Cp-Ti irrespective of heat treatment as well as rise in laser pass commonly reduce wear rates. The microstructures revealed dendrite shaped and morphology of columnar deposit around primarily matrix of α-titanium.

A process of reactive deposition AM was adopted by Traxel and Bandyopadhyay [45] for maintaining Ti-Zr-BN composite parts using commercially pure titanium (Cp-Ti) with addition of Zr and BN. This was aimed at improving elevated temperature and wear resistance abilities if TMC using LENS. The as-fabricated BN-containing components shows TiB_2, TiN and TiB as reinforcement with SEM image of CpTi-BN and CpTi-Zr-BN presented in **Figure 2** below. Zr-addition displays a combination of composites of composites and alloys leading to high hardness and ultimate compressive strength (UCS) with enhanced wear resistance. This method is expected to be used in creating novel coatings and structures from vast powder feedstocks to develop the bulk and surface characteristics of titanium related metals.

Effects of thermal history and build direction were studied by Mantri and Banerjee [48] on β-Ti alloys containing Mo-12 wt% and V-20 wt%, produced

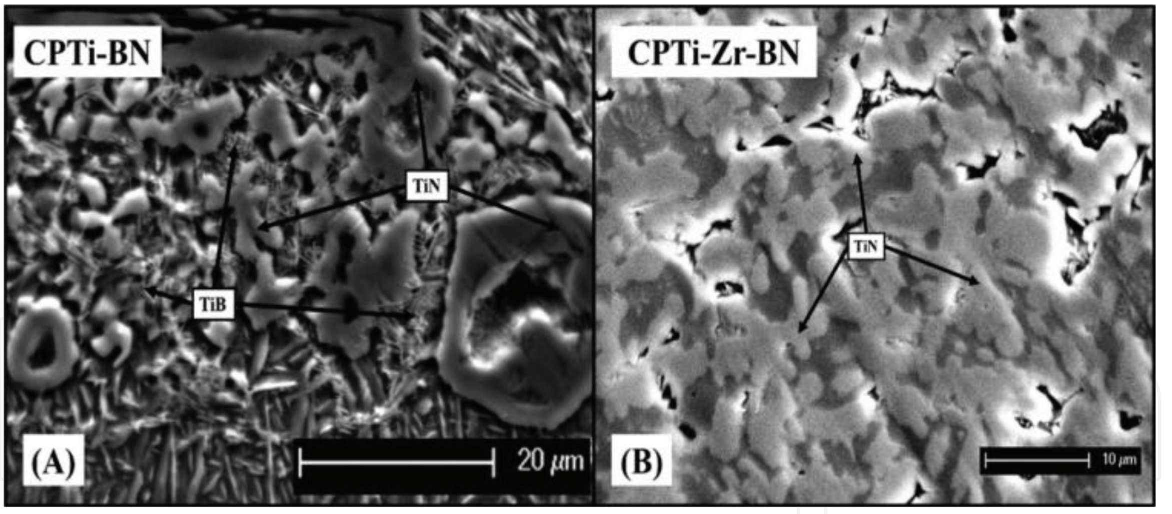

Figure 2.
SEM images of (A) CPTi-BN [45] (B) CPTi-Zr-BN [45] compositions.

through LENS technique. A specific single β-phase is identified in 20 wt% V while the dual-phase microstructure in Ti-12 wt% Mo system revealed α-phase in β-grain morphology. This was accredited to the build directions that had different thermal cycles at various portion of the builds.

In the work of Li et al. [47], LAM was used to fabricate Ti-6Al-2V-1.5Mo-0.5Zr-0.3Si alloy in order to examine tensile strength and microhardness of the alloy. Mixed columnar β-grains with no equiaxed microstructure was observed for as-deposited alloy. The addition of Zr, Mo and Si causes increase in microhardness value because of hardening effect of their solid solution. Also noticed, was the rise in ductility in comparison to Ti-6Al-4V.

Song et al. [5] reported the titanium alloy to fabricate a prosthetic beak as shown in (**Figure 3**) for a bird (*Grus japonensis*) using SLM. A model was first developed for the titanium alloy customized beak and was successfully completed to save the endangered bird.

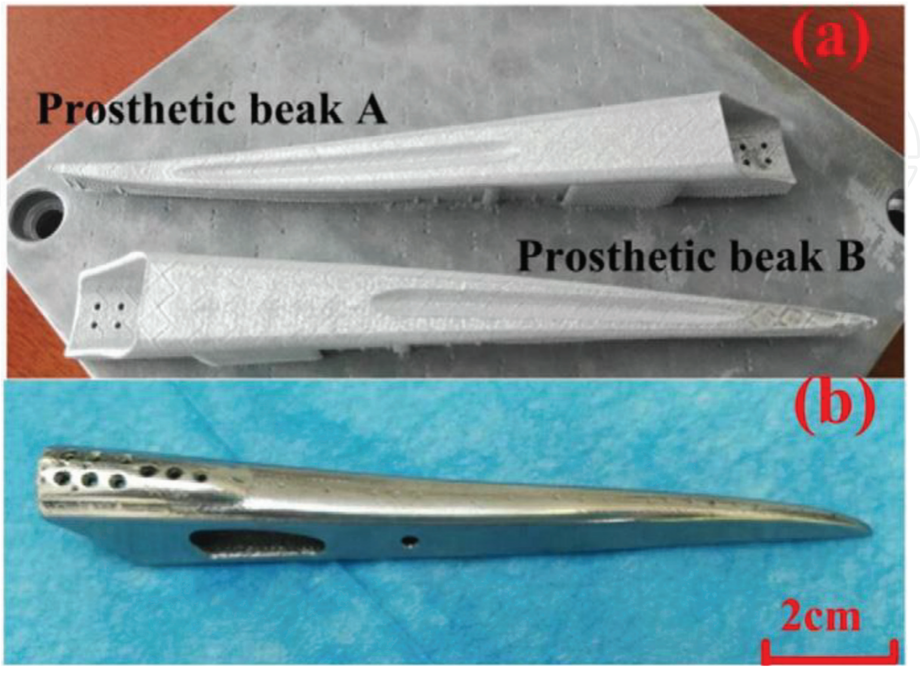

Figure 3.
SLM fabricated prosthesis beaks: (a) as-fabricated (b) polished and surface treated [5].

A comparative study of SLM and electron beam melting (EBM) carried out by Zhao et al. [54] to fabricate Ti-6Al-4V parts. Both components largely contained $\alpha + \beta$ and α' phase, respectively. SLM samples had higher tensile strength but lower ductility than EBM fabricated parts. Even though porosity was observed in both cases it was much higher in SLM parts. While generally, samples fabricated in the vertical direction had increased ultimate tensile strength, yield strength, and improve ductility than those in the horizontal orientation.

Direct metal deposition (DMD) has been used by Pouzet et al. [55] to build samples with varying volume fractions of TiB + TiC. The Coaxial deposition process fabricated TMC from powder mixture of T-6Al-4V + B4C. Pure and consistent Ti-6Al-4V-TiB microstructure was noticed and boron isolation during solidification of β-Ti resulted in grain refinements. At low B4C, TiC was not observed which was ascribed to high solubility of C in α-Ti at high solidification rate leading to decreased tensile strength at elevated and room temperature.

2.2 Laser additive manufacturing (LAM) of titanium aluminides

TiAl are known to be favorable for high-temperature component because of their high strength-to-weight ratio, high melting point, attractive creep and superior modulus of elasticity [56]. Recently, TiAl-based alloys have been effectively applied in aircraft engine productions with increase in demand for these alloys expected in the near future [57].

Microstructure and phase composition are immensely determining the properties of intermetallic TiAl-based alloys. Elements like Mo, V, Zr, Mn, Nb, Cr, Ni and Fe are known to be employed in developing enhanced mechanical properties for TiAl [58, 59]. The site effects for most of the elements remains unchanged with the different alloy compositions. However, Cr, Mn and V site substitution vary subject to Ti:Al ratio [59]. It is commonly accepted that a microstructure of equiaxed fine grains are desirable to enhance strength and ductility whereas coarse microstructure of fully lamellar is better for high creep.

The lack of ductility of TiAl at room temperature makes it problematic to machine and fabricate components by traditional methods. AM is very promising to incorporating design freedoms and processing when building components [60]. LENS and selective laser melting/sintering (SLM/SLS) are primarily known as LAM techniques. Various AM technologies are called by their trade names from the manufacturers or company of establishments [61]. A laser engineered net shaping (LENS) Optomec 850R machine for AM system is shown in **Figure 4**. This technique is suitable for manufacturing and realization of complex geometries with reduced lead time and material loss [62]. The process uses a focused laser beam for melting and fusion producing 3D parts from feedstock powder. Apart from building components (**Figure 5**), it refurbishes components through a process called laser cladding. This is believed to be the state-of-the-art technique for aero engine parts repairing [63].

For aerospace components materials, when compared with conventionally applied materials like Ni-based superalloys, TiAl is far harder and offers close to 50% weight savings. This results in decrease cost of turbine operations and emission levels due to highly efficient fuel usage [63]. Advances in recent development techniques has led to collaborations among manufacturers. This is made possible to fabricate turbine blades using electron beam melting (EBM) from pre-alloyed Ti4822 powder, presently employed in GEnx engines [60, 64].

For aerospace components materials, when compared with conventionally applied materials like Ni-based superalloys, TiAl far harder and offers close to 50% weight savings. This results in decrease cost of turbine operations and emission

Figure 4.
LENS Optomec 850R additive manufacturing system.

Figure 5.
LENS Fabricated Object.

levels due to highly efficient fuel usage [63]. Advances in recent development techniques has led to collaborations among manufacturers. This is made possible to fabricate turbine blades using electron beam melting (EBM) from pre-alloyed Ti4822 powder, presently employed in GEnx engines [60, 64].

DED was adopted by Hoosain et al. [10] to create clads of γ-TiAl using in-situ elemental Ti and Al powder. The purpose of the study was to optimize formation of γ-phase during laser processing through mass flow rates. Depending on flow rate of Al and heat treatment both duplex and lamellar phases are observed. Also, Al content largely determines the microhardness and twinning existence. In another work, Hoosain et al. [56] investigated the consequences of Al flow rate on microstructure of in-situ alloy composition. The γ-TiAl was compared with Ti4822, a duplex phase microstructure was observed as Al feed rate increase. Fine lamellar grains were not generated for heat treatment temperature at 1200°C because it was below the temperature of α-transus. **Figure 6** presents the microstructure of commercial GE alloy Ti-48Al-2Cr-2Nb alloys.

In the feasibility study carried out by Dilip et al. [65], Ti-6Al-4V and Al powder was employed to samples of TiAl using binder jetting AM and reactive sintering.

Initially, Al_3Ti formation was obtained in the liquid phase due to Ti64 and Al reaction. Afterwards, TiAl was formed has diffusion of Al continues with sintering time. Other intermetallic together with TiAl phases were obtained in the final microstructure.

Todai et al. [41] presented a study to manipulate Ti4822 alloy microstructure fabricated through EBM process. Duplex-like and γ-bands of layered microstructure were formed by recurring heat treatment of melt pool area. The angle of building substantially makes the tensile elongation and yield strength (YS) to vary. The XRD patterns of the EBM built Ti-48Al-2Cr-2Nb alloy in different directions are displayed in **Figure 7**. The anisotropy of YS reduces as temperature rises. The heat treatment at 700°C gave the highest YS which show decrease in value as temperature rises. EBM was also adopted by Murr et al. [66] in fabricating TiAl from precursor powders to investigate to hardness and microstructure produced. Microstructure of α_2-Ti_3Al was noticed for powder precursor whereas lamellar colony at γ/α_2 with equiaxed γ-TiAl was obtained for EBM samples. It was reported that the EBM-fabricated TiAl had microhardness of ~4.1GPa which makes the YS far exceed that of EBM-fabricated Ti64.

Selective electron beam melting (SEBM) was adopted by Chen et al. [67], to investigate the microstructural variations of TiAl alloy samples and their impact on microhardness. A near lamellar structure was observed TiAl alloys. During the

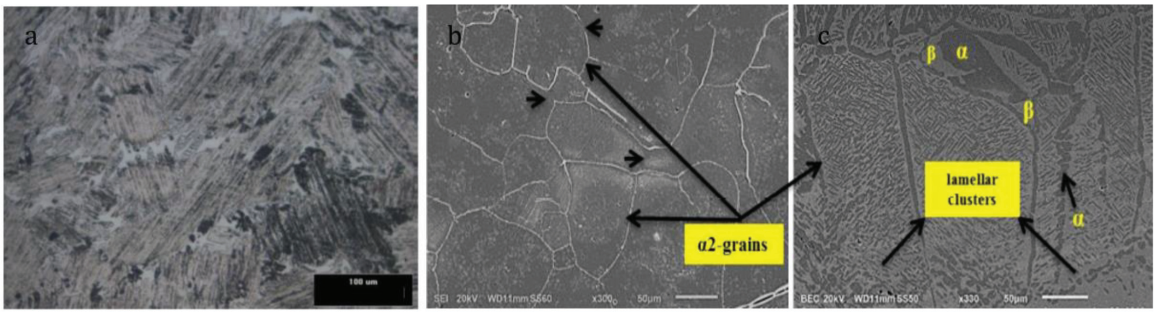

Figure 6.
Microstructure of the commercial GE alloy Ti-48Al-2Cr-2Nb (a) showing the lamellar type microstructure [56] and heat treated of at (b) 1200°C [10] and (c) 1430°C [10].

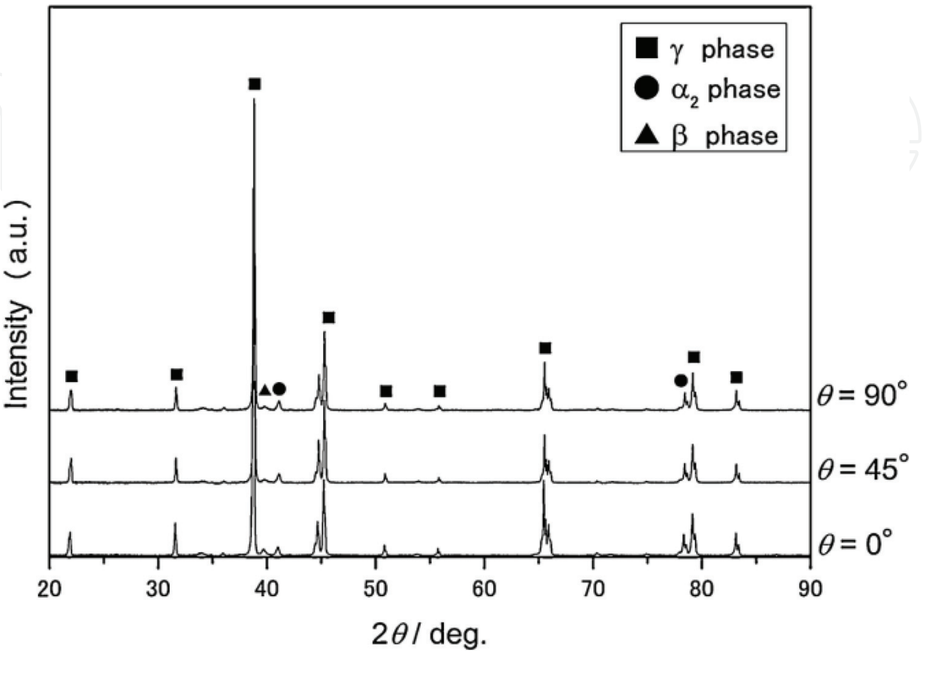

Figure 7.
XRD pattern of Ti-48Al-2Cr-2Nb alloy specimens fabricated by EBM at 0°, 45° and 90° [41].

process, three phase transformation of $\alpha_2 + \gamma \rightarrow$ B2, $\alpha_2 \rightarrow$ B2, $\alpha_2 \rightarrow \gamma$ was noticed. An increase in hardness was ascribed to rapidly raising quantity of lamellar colonies α_2/γ has the built height increases.

The structure of TiAl alloys was examined by Li et al. [68] for detailed characterization of SLM processed Ti-45Al-2Cr-5Nb alloy. Anisotropy of microstructure were obtained has the sides contained columnar grains while the top showed equiaxed microstructure. The processed sample was overshadowed with high angle grain boundaries (HAGBs) which is favored by the energy density. Also, evenly dispersed minute quantities of B2 and γ phases (nano meters range) were found in α_2 matrix γ and B2 phase reduces with raising energy density whereas α_2 content increases.

Sharman, Hughes and Ridgway [61] stated that previous works on LAM had concluded that it was merely impossible to manufacture component of TiAl that are crack free without additional heating to influence the solidification process. It was demonstrated that by defocusing the laser across build surface heats the particles ahead of entering melting zone. Hence, decrease rate of cooling lower than the critical level that permits crack formation.

Oxide dispersion strengthen (ODS) has been used by Kenel et al. [14] to fabricate Ti-45Al-3Nb- $< 0.2Y_2O_3$ at.% and studied the microstructure. The traditional microstructure of $\alpha_2 + \gamma$ and near-lamellar were observed. The ODS-TiAl alloy displays greater hardness than ones without the reinforcement. β-solidifying TiAl was studied by Gussone et al. [69] fabricated by SLM of γ-TiAl pre-alloyed powder. Under cooling of β occurred due to tremendous Al loss leading to β/B2 microstructure. During SLM and hot isostatic pressing (HIP), the raise in content of oxygen make the sample less ductile.

Seifi et al. [70] conducted and experiment to evaluate the mechanical properties and microstructure of EBM γ-TiAl with HIP. The two conditions presented microstructure of heterogenous interchanging γ-grains of coarse and fine bands. It is worthy to note that the EBM samples revealed microcracks at secluded sections all over the builds. The consequence of beam current on microstructure and grain boundary orientation had been studied by Yue et al. [71] for Ti-47Al-2Cr-2Nb manufactured by selective electron beam melting (SEBM). Increases beam current resulted in resulted in microstructural transformation to near-γ structure to fine duplex phase and B2-phase volume fraction steadily rises. Also, HAGB increases progressively with beam current while the low angle grain boundary (LAGB) reduces.

In establishing a relationship among scan speed, microstructure and mechanical properties, Li et al. [18] fabricated Ti-45Al-2Cr-2Nb parts using SLM. The grain size reduces with laser scan while crystallographic topography basically remains unchanged. The phases of B2 and γ rises with increased scan speed whereas α_2-phase is lowered. It was also reported that nanohardness and compressive strength rises with improved scan speed for the SLM TiAl alloy.

Chen, Yue and Wang [72] studied SEBM sample using various scan speed to produce Ti-47Al-2Cr-2Nb alloys. Microstructural changed occurred to duplex from near-γ structure as the scan speed rises. However, both α_2 and B2 phases are homogenously dispersed in the matrix of γ. Ultimate compressive strength (UTS) of SEBM-produced TiAl alloy generally increased with the scanning speed.

Statistical examination was used by Shi et al. [73] to optimize process parameter of SLM Ti-47Al-2Cr-2Nb on Ti-6Al-4V substrate. It was understood that unsuitable amalgamation of process parameters would lead to instability of melt pool, cracks balling and other defects. To optimize the process, Al loss need to be taken into account. The ideal process parameter obtained was able to build TiAl components with 97.34–98.95% densities.

3. Development of titanium aluminide composites for aerospace applications

LENS technique uses high-powered laser to deposit materials and it has been significant in repairing and building of metallic components [74]. Nevertheless, the qualities and mechanical properties of built components are greatly affected by imperfections like porosity, crack cavitation and inhomogeneous microstructure. Composite are of very high demand in aerospace industry because of requests for property combination like high stiffness, fracture toughness, strength, oxidation resistance and lightweight. Moreover, the impetus for composites in aerospace is the ever-increasing demand, thus substitute for metal alloys as weight reduction, cost-saving and fuel efficiency [75]. The aviation industry needs components made with materials with high thermal and mechanical properties at reduced cost [75, 76]. Presently, AM of TiAl is developing, but cracks do emanate due to the integrally brittle nature of the material [77].

According to Kablov et al. [78], the qualitative improvement of the technical and performance indicators of aviation gas turbine engines (AGTEs) and power plants largely depends on the implementation of new materials with a previously unachieved combination of properties. It was established that alloying intermetallic titanium ortho alloy with gadolinium in the amount of 0.1 at.% results to the rise in strength at room temperatures owing to the realization of the mechanism of dispersion strengthening with finely dispersed gadolinium oxides [78].

A crucible-less technique was adopted by Kartavykh et al. [79] to cast TiAl alloy with composition with composition of Ti-44Al-5Nb-3Cr-1.5Zr (at.%) and high-gradient float zone (FZ) re-solidification. Dual phase of $\gamma + \alpha_2$ lamellar with small quantities of B2 + γ was observed for the FZ processed alloy. This alloy had high tensile strength which is promoted by Cr accumulation in B2 phase.

A third-generation Ti-43.5Al-4Nb-1Mo-0.1B (TNM) fabricated with casting +HIP was studied by Dahar, Tamirisakandala and Lewandowski [27] to determine the influence of thermo mechanical treated specimen and applied force fracture behavior. Noteworthy alterations of phases were noticed due to the processing.

A coating of TiAl resistant to oxidation was developed by Sienkiewicz et al. [80], for thermal shield structures of material. A coating of titanium-aluminum-silicon system of varying chemical configurations was produced through warm spraying. Silicide of $Ti_5(Si,Al)_3$ was observed for two kind of morphologies. Generally, the coating shows attractive cyclic and isothermal resistance.

A complete processing chain develop by Juechter et al. [81], to demonstrated that Ti-45Al-4Nb-C processed by selective electron beam melting (SEBM) could be applied in manufacturing turbocharger wheels. This was made possible by enhanced optimization scan approach coupled with heat treatment.

The microstructures and mechanical properties of Ti6Al4V and Ti45Al7Nb powder mixtures in ratio 1:1 was studied by Wenjun, Chao and Feng [82] using Electron beam selective melting (EBSM) to build samples resulting in Ti22Al3.5Nb2V alloy. Two distinct portions of microstructure were noticed, a dual ($\alpha_2 + \beta$) phase and martensite portion. The dual phase region had lower microhardness value compared to the other portions.

The effects of carbon (C) addition was studied by Klein et al. [76], on γ-TiAl based alloys. Generally, C induces more α_2-phase formation and reduces β_o-phase. However, substantial hardening of γ and α_2 phases occurred with rise in C concentration.

Laser cladding TiN/Ti_3Al intermetallic composite coatings have been successfully used to increase the elevated temperature resistance to oxidation and mechanical properties of Ti6Al4V alloy [83]. The clads were largely constituted by phases of α-Ti, Ti_3Al and TiN. The intermetallic of TiN/Ti_3Al are high oxidation resistant with microhardness far above the value of Ti6Al4V.

An examination of the connection between boron (B) content and microstructural characteristics of TiAl/B (Ti-46.5Al-2.5Cr-2Nb-0.5Y/B) composites produced by SLM was carried out [84]. The grain size reduces as B increases but the HAGBs also rises with B. Owing to grain refinement strengthening system, the highest value of 1610.53 MPa and 5.17% was recorded for compressive strength and strain respectively.

The effects of Nb, Ta and Zr had been investigated by Bresler et al. [85], for Ti-44Al-5X (X = Nb, Ta, Zr) to examine creep properties (**Figure 8**). All alloying elements mostly improve creep performance substantially and reduce interspacing of α_2/γ while enhancing stability of microstructure.

TiAl-based alloys of two molybdenum (Mo) content was fabricated by Jiang et al. [86] through vacuum levitation melting (VLM). Mo addition is understood to refine lamellar size colonies. It also encourages twining capabilities and reduces cracks in β phase.

Laser metal deposition (LMD) was adopted by Carrullo, Falcón and Borrás [87], to analyzed films produced on Ti48Al2Cr2Nb coating during oxidation through optimization of parameters. The coatings demonstrated high oxidation resistance at 800°C. The layers of oxides formed showed complex microstructure and development of consecutive layers on coating.

Ambient temperature mechanical characteristics were evaluated by Dai et al. [88], for coatings of Ti-Al-Si on the substrate of Ti6Al4V through laser surface alloying. Thermal expansion between coating and substrate resulted in crack formation and propagation. The coating basically consists of Ti_5Si_3 reinforcement in Ti-Al-phase. Si content increase causes resultant rise in brittle Ti_5Si_3 which had increased hardness than Ti-Al. The process of high-temperature oxidation resistance of Si in Ti-Al-Si system coatings involves increased refining of oxide grains and boosting the creation of Al_2O_3.

An investigated of microstructure carried out by Maliutina et al. [89], on laser cladding of TA6Zr4DE using Ti48Al2Cr2Nb powders. The coatings had γ-TiAl and α_2-Ti_3Al phases of fully lamellar microstructure. The occurrence of niobium as an

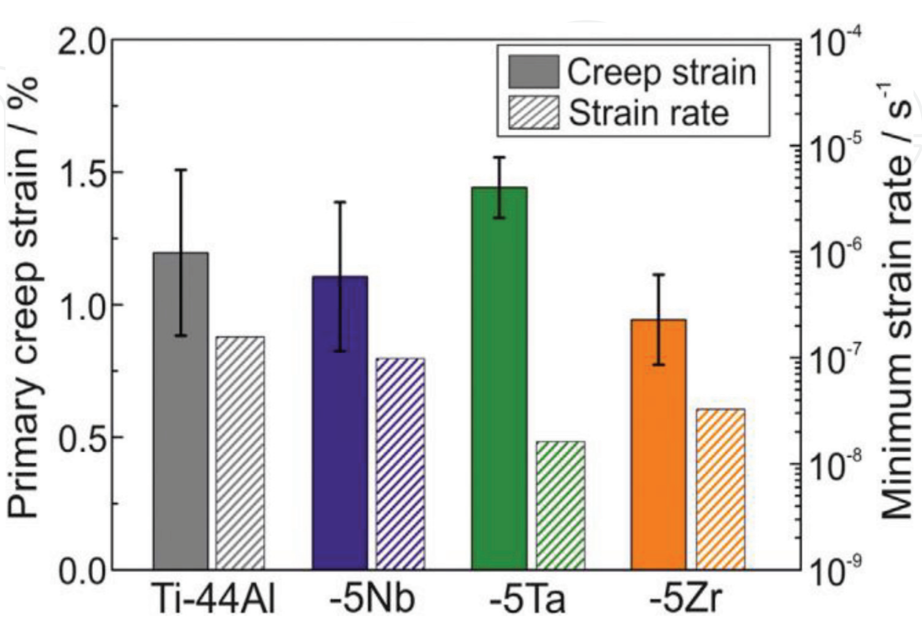

Figure 8.
Primary creep regime and minimum strain rate of binary Ti-44Al and Ti-44Al-5X (X = Nb, Ta, Zr) alloys, tested at 900°C and 100 MPa [85].

alloying element restrains the oxygen dispersion making impact in the creation of more favored alumina films.

LENS was employed by Zhang and Bandyopadhyay [90], to deposit Ti6Al4V and Al_2O_3 powders on Ti6Al4V substrate. For the pure Ti6Al4V, α-laths of Widmanstätten Ti was obtained while Ti6Al4V + Al_2O_3 parts revealed equiaxed grains with non-melted Al_2O_3. Microhardness results showed that Al_2O_3 section possessed the maximum hardness value followed by Ti6Al4V + Al_2O_3 sections.

Direct laser cladding (DLC) of Ti45Al5Nb0.5Si had been studied by Majumdar et al. [91], to determine the consequence of varying parameters on titanium aluminide. Dual phase $\alpha_2 + \gamma$ was revealed in DLC Ti45Al5Nb0.5Si alloy. The processing parameters had little effect on the microhardness of the clad. Rise in Si quantity improved the propensity to produce cracks.

4. Heat treatment of laser processed titanium aluminide components

The microstructural evolution of γ-TiAl clearly affects the end products mechanical properties as a result of processing and post-processing operations. Dependent on the characteristics anticipated for parts, several techniques could be utilized to fix microstructure. It has been reported that lamellar of coarse grains display comparatively superior fracture toughness, creep but lack ductility, notably at room temperature whilst duplex of fine grains connotes low fracture toughness, creep resistance nonetheless modest ductile property [27].

SLM of Ti-44.8Al-6Nb-1.0Mo-0.1B was investigated by Gussone et al. [62] and influence of heat-treatment during and after fabrication. The results showed that considerable changes stimulated by heating the unstable Ti-44.8Al-6Nb-1.0Mo-0.1B varies sharply. The initial heat treating of samples produces microstructures exemplified by increased orbicular γ and β/βo at the α_2/γ boundaries colony.

Alloy Ti-47Al-2Nb-2Cr (at%) fabricated through selective electron beam melting (SEBM) by Guangyu et al. [92], examined the influence of post processing heat treatment on microstructure. Lamellae microstructure was revealed for the samples (**Figure 9**) because of SEBM cyclic heating. Hence, transformation of phases was clearly through β-phase. Though, various structures are gotten at different temperatures, oil quenching at 1250°C+ heating to 1200°C for 2 h produces a refined and homogeneous microstructure.

Klein et al. [93] investigated the microstructural formations of Ti-Al-Nb-Cr-Mo in understanding the requirements for controlling the microstructure formation and concomitant properties. Upon annealing, γ-platelets arise initially from the precipitating β_o-phase. Cr and Mo are repelled throughout the γ-grain development.

The influence of annealing temperature was investigated by Ren et al. [19], on Ti-45Al-8.5Nb formation of controlled in lamellar structure. The regulated α_2 lamellae appears in alloys annealed at lesser than 650°C and vanishes beyond 700°C. Extensive hardening stimulates O phase on α_2 lamellae and the $\gamma/(\alpha_2 + O)$ been obtained attributed to refined α_2 lamellae. The schematic of the heat treatment procedure is depicted in **Figure 10** below.

Analysis of microstructure of high-Nb TiAl alloy carried out by Qiang et al. [94], for Ti-45Al-8.5Nb-0.2 W-0.2B-0.02Y (at.%) resulting from numerous cooling rate. The transformation path $\alpha \rightarrow \alpha_2 + \gamma$ for lamellar microstructure is controlled chiefly by its rate of cooling. Fast rate of cooling causes the retention of α/α_2 phase of supersaturated microstructure. It was suggested that a rapid cooling rate and slow rate of cooling for $\alpha \rightarrow \alpha_2 + \gamma$ and $\beta \rightarrow \alpha$ transformation respectively.

In the repair of defective or worn blade parts by Rittinghaus et al. [95], LMD of TNM™ β-containing alloy with composition of Ti-43.5Al-4Nb-1Mo-0.1B (at.%) was

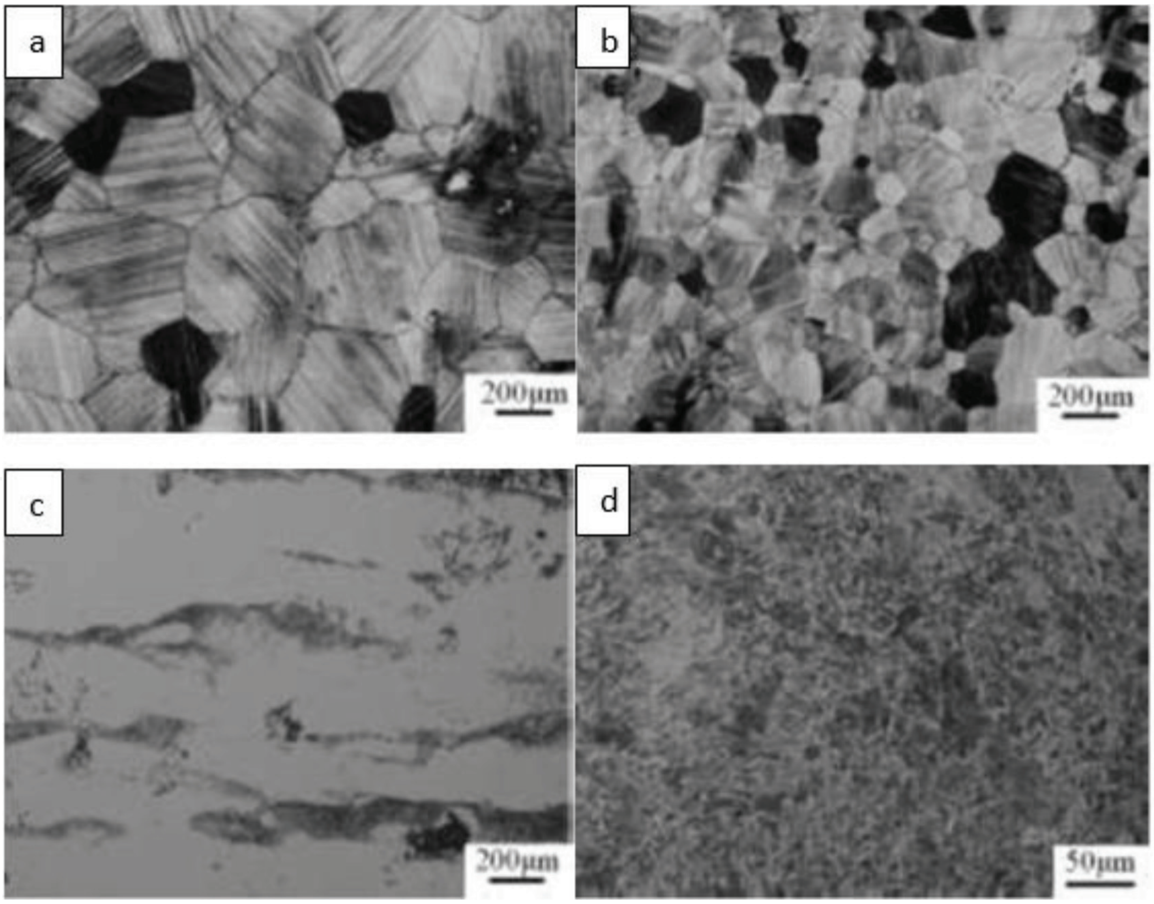

Figure 9.
Microstructures of heat-treated Ti-47Al-2Nb-2Cr alloy at (a) 1250°C for 2 h air cooled (b) 1300°C for 10 min air cooled (c) 1250°C for 10 min oil quenched (d) 1250°C for 10 min oil quenched followed heat treating at 1200°C for 2 h air cooled [92].

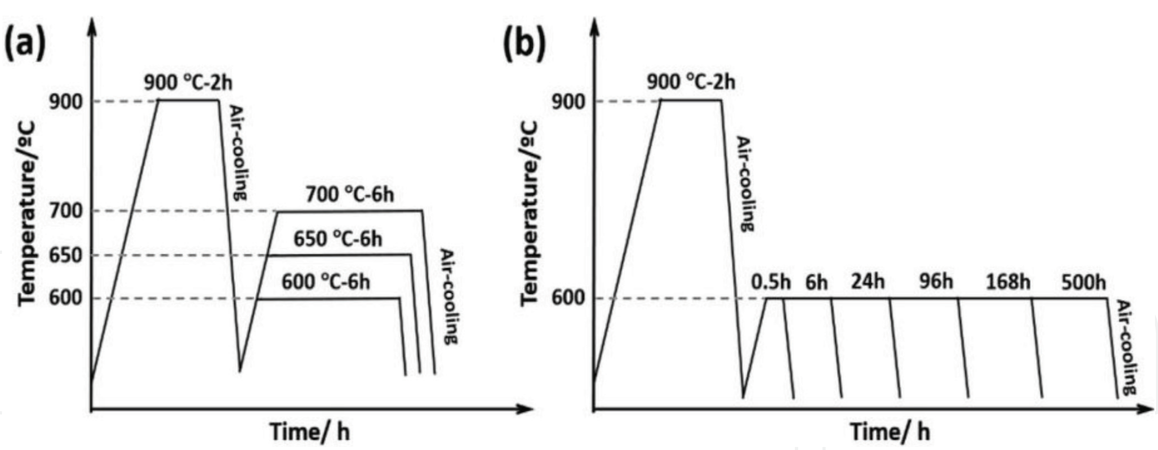

Figure 10.
Heat Treatment Pattern Adopted by Ren et al. 19 for the γ-Ti-45Al-8.5Nb alloy annealed at 900 oC for 2 hrs followed by air cooling with (a) annealing at 600 °C, 650 °C and 700 °C for 6 hrs each followed by air cooling (b) isothermal annealing at 600 °C for annealing time range from 0.5 to 500 hrs followed by air cooling.

studied. Small fraction of β_o reduces the microhardness of the LMD alloy. Lamellar orderings are moderately greater in the LMD microstructure because annealing is achieved in the (γ + α) phase with noticeable coarsening of the non-melted γ lamellae.

Also, phase transformations were examined by Kastenhuber et al. [28] for β-containing γ-TiAl based alloy in gas atomization of fast cooling. Initial variations of composition caused a primary β-phase, indicating to an uninterrupted escalation of the Al and lessening of Nb, Mo and Ti at the previous β-grain boundaries. Therefore, following L → L + β reaction the solidification path continues unevenly, subject to Al-content and quantities of Nb and/or Mo. At room temperature the γ-phase appears in three different morphologies.

The consequence of heat treatments was studied by Li et al. [96], to evaluate grains features, transformation of phases and hardness of Ti-45Al-2Cr-5Nb (at.%) produced through SLM. The grains of heat-treated parts are overshadowed with HAGBs that rises as temperature of annealing increases. SLM-fabricated alloy has $D0_{19}$ structure of α_2 phase but the B2-phase is a bcc structure and γ-phase illustrate a $L1_o$ (bcc) structure.

The microstructural evolution and room temperature fracture toughness β-solidifying TiAl alloy studied by Chen et al. [30], for Ti-45Al-2Nb-1.5V-1Mo-0.3Y (at.%). Fine near-lamellar containing majorly of fine grains and combinations of γ + β phases with lamellar colony boundaries. The precipitation of fine β and γ grains is deemed an inherent toughness system due to α_2/β and α_2/γ boundaries creating limited displacement movement successfully.

The influence of heat treatment was studied by Tebaldo and Faga [97], on hardness of Ti48Al2Nb2Cr manufactured through EBM technology. It was noticed that only minor different in density occurred due heat treatment and micro porosity. Near-γ with equiaxed lamellar was obtained for samples not heat treated and fully lamellar achieved for heat treated samples. It was concluded that the developed alloy would be appropriate for manufacturing components in aircraft engines.

An incorporation of both HIP and heat treatment was developed by Chen et al. [13], to enhance mechanical properties of TiAl alloy. Corresponding increment in elongation and YS was noticed for both duplex and lamellar structures. Reduction in TiAl alloy mechanical properties was evident from the observed microcracks. However, the combined production method showed a microcrack free microstructure, thereby enhancing the properties. Illustration of the processing routes are shown in **Figure 11**.

Mechanical and microstructure governing techniques was investigated by Zhao et al. [98], for Ti-46Al-2Nb-2V-1Mo-Y (at%). The α + β + γ phase pre-treatment by annealing actually gave raise to the breakdown of lamellar α/γ structures. Fully-lamellar was attained with prolong annealing whereas for two-step process,

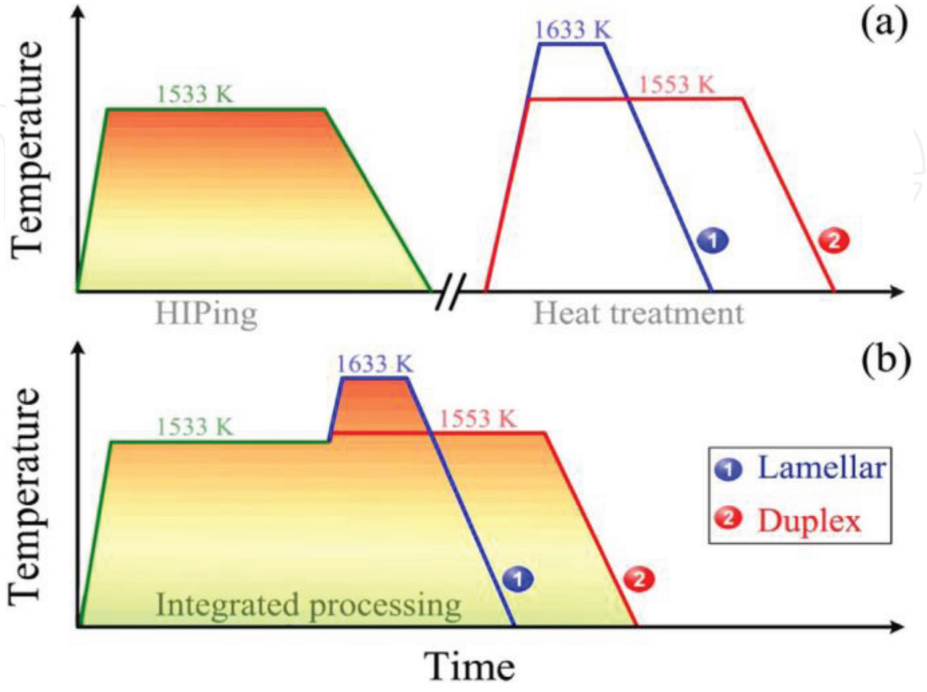

Figure 11.
The processing routes adopted by Chen et al. [13] (a) separately (b) combined processing.

duplex phase were observed. The duplex phase reveals greater room temperature tensile property, whilst fully-lamellar had better strength.

The influence of cooling rate was investigated by Fan et al. [99], on mechanical and microstructural attributes of Ti-49Al alloy. Increased rate of cooling results in reduction of interlamellar and dendrite spacings. Whereas rise in cooling rate causes corresponding improvement in tensile strength and hardness values. Consequently, microhardness value rises as tensile strength increases for Ti-49Al (at.%) directionally solidified alloy.

5. Challenges and critical issues

According to Bünck et al. [58], recent manufacturing processes for aerospace parts are expected to be well developed and cost-effectively competitive methods. LAM parts have high surface roughness and structural inhomogeneity and usually necessitate supplementary treatments to diminish irregular microstructure. Inadequate ambient temperature ductile property of TiAl alloys deters processing. Even during forging using isothermal process, dies are preserved at considerably high temperatures. Practical issue still to be stopped is the reactivity of melting crucible with TiAl, besides the matters of cost [25]. Novel methods are required that permit the modification of satisfactory amount of ductility though preserving the exceptional strength and creep characteristics that aforementioned research works has unlocked. The solution to unravel this difficulty rests in essential consideration of fundamental relationship between the properties and microstructure mechanisms. Grain morphology control is a challenging issue for LAM of large metallic components. Numerous practices have extensively considered the additional characteristics of TiAl-based aerospace parts, comprising the practice of surface modeling, application of coatings and heat-treatment.

Presently, LAM has the prospective to develop typical manufacture techniques, specifically in creating of small size of extremely complicated components [100]. Manufacturers have previously presented low-pressure turbine blades (LPTB) of TiAl alloy in aero engines and more interest is shown for the development of TiAl, demonstrating the distinctiveness of the alloy. This is with a view that engine efficiency would be substantially better-quality, indicating decreased fuel utilization, CO_2 emission and noise. Consequently, increases stress is envisaged for TiAl-LPTBs and necessitates adjusting processing routes to produce functional materials.

LAM is suggested to have benefits for aircraft engine components because it can easily translate designs to 3D component, produce customized parts and functional designs with complex and intricate features [36]. It also has potential of manufacturing parts with no waste, lightweight and minimal lead time of manufacturing. Hence, it has the ability to be exceptional scalable and manufacture final product with little or no post-processing.

6. Summary and conclusions

Based on the reviewed works, it can be generally deduced that LAM processing of titanium aluminide suffers several set-backs militating against its wider acceptance in aerospace application. Although, it has attractive features making it to be qualified as a candidate material for aerospace applications, the processing and post-processing problems still needs to be looked into. It is expected that combined processes of alloying and heat treatment (in-situ and ex-situ) could result in appreciable ductility while maintaining other mechanical properties. Consequently, researchers would be able to develop a mechanism of fabricating TiAl with better room and elevated temperature properties.

Acknowledgements

The authors would like to acknowledge the financial support of African Laser Centre-National Laser Centre; Council of Scientific and Industrial Research (ALC-NLC; CSIR), Project Number LHIP500 Task ALC S100.

Author details

Sadiq Abiola Raji[1*], Abimbola Patricia Idowu Popoola[1], Sisa Leslie Pityana[1,2], Olawale Muhmmed Popoola[3,4], Fatai Olufemi Aramide[1,5], Monnamme Tlotleng[2] and Nana Kwamina Kum Arthur[2]

1 Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, Pretoria, South Africa

2 National Laser Centre, Council of Scientific and Industrial Research (NLC-CSIR), Pretoria, South Africa

3 Department of Electrical Engineering, Tshwane University of Technology, Pretoria, South Africa

4 Centre for Energy and Electric Power (CEEP), Tshwane University of Technology, Pretoria, South Africa

5 Department of Metallurgical and Materials Engineering, Federal University of Technology, Akure, Ondo State, Nigeria

*Address all correspondence to: rajchandy2355@gmail.com

References

[1] Zhang M, Shen M, Xin L, Ding X, Zhu S, Wang F. High vacuum arc ion plating TiAl coatings for protecting titanium alloy against oxidation at medium high temperatures. Corrosion Science. 2016;**112**:36-43. DOI: 10.1016/j.corsci.2016.07.005

[2] Sallica-Leva E, Jardini AL, Fogagnolo JB. Microstructure and mechanical behavior of porous Ti–6Al–4V parts obtained by selective laser melting. Journal of the Mechanical Behavior of Biomedical Materials. 2013;**26**:98-108. DOI: 10.1016/j.jmbbm.2013.05.011

[3] Hu Y, Ning F, Wang H, Cong W, Zhao B. Laser engineered net shaping of quasi-continuous network microstructural TiB reinforced titanium matrix bulk composites: Microstructure and wear performance. Optics & Laser Technology. 2018;**99**:174-183. DOI: 10.1016/j.optlastec.2017.08.032

[4] Mohammad A, Al-Ahmari AM, Balla VK, Das M, Datta S, Yadav D, et al. In vitro wear, corrosion and biocompatibility of electron beam melted γ-TiAl. Materials & Design. 2017;**133**:186-194. DOI: 10.1016/j.matdes.2017.07.065

[5] Song C, Wang A, Wu Z, Chen Z, Yang Y, Wang D. The design and manufacturing of a titanium alloy beak for Grus japonensis using additive manufacturing. Materials & Design. 2017;**117**:410-416. DOI: 10.1016/j.matdes.2016.11.092

[6] Hu Y, Zhao B, Ning F, Wang H, Cong W. In-situ ultrafine three-dimensional quasi-continuous network microstructural TiB reinforced titanium matrix composites fabrication using laser engineered net shaping. Materials Letters. 2017;**195**:116-119. DOI: 10.1016/j.matlet.2017.02.112

[7] Liang YJ, Liu D, Wang HM. Microstructure and mechanical behavior of commercial purity Ti/Ti–6Al–2Zr–1Mo–1V structurally graded material fabricated by laser additive manufacturing. Scripta Materialia. 2014;**74**:80-83. DOI: 10.1016/j.scriptamat.2013.11.002

[8] Santhosh R, Geetha M, Rao MN. Recent developments in heat treatment of beta titanium alloys for aerospace applications. Transactions of the Indian Institute of Metals. 2017;**70**(7):1681-1688. DOI: 10.1007/s12666-016-0985-6

[9] Tlotleng M, Lengopeng T, Seerane MN, Pityana SL. Effects of heat-treatment on the microstructure of TiAl-Nb produced with laser metal deposition technique. In: Proceedings of the Materials Science & Technology, October 8–12, 2017. Pittsburgh, Pennsylvania USA: David L. Lawrence Convention Center; 2017. DOI: http://hdl.handle.net/10204/9874

[10] Hoosain S, Pityana S, Freemantle C, Tlotleng M. Heat treatment of in situ laser-fabricated titanium aluminide. Metals. 2018;**8**(9):655. DOI: 10.3390/met8090655

[11] Kartavykh AV, Asnis EA, Piskun NV, Statkevich II, Gorshenkov MV, Korotitskiy AV. A promising microstructure/deformability adjustment of β-stabilized γ-TiAl intermetallics. Materials Letters. 2016;**162**:180-184. DOI: 10.1016/j.matlet.2015.09.139

[12] Cheng J, Yu Y, Fu L, Li F, Qiao Z, Li J, et al. Effect of TiB2 on dry-sliding tribological properties of TiAl intermetallics. Tribology International. 2013;**62**:91-99. DOI: 10.1016/j.triboint.2013.02.006

[13] Chen L, Zhu L, Guan Y, Zhang B, Li J. Tougher TiAl alloy via integration of hot isostatic pressing and heat treatment. Materials Science and

Engineering A. 2017;**688**:371-377. DOI: 10.1016/j.msea.2017.02.028

[14] Kenel C, Dawson K, Barras J, Hauser C, Dasargyri G, Bauer T, et al. Microstructure and oxide particle stability in a novel ODS γ-TiAl alloy processed by spark plasma sintering and laser additive manufacturing. Intermetallics. 2017;**90**:63-73. DOI: 10.1016/j.intermet.2017.07.004

[15] Xu WC, Huang K, Wu SF, Zong YY, Shan DB. Influence of Mo content on microstructure and mechanical properties of β-containing TiAl alloy. Transactions of Nonferrous Metals Society of China. 2017;**27**(4):820-828. DOI: 10.1016/S1003-6326(17)60094-3

[16] Cho K, Kobayashi R, Oh JY, Yasuda HY, Todai M, Nakano T, et al. Influence of unique layered microstructure on fatigue properties of Ti-48Al-2Cr-2Nb alloys fabricated by electron beam melting. Intermetallics. 2018;**95**:1-10. DOI: 10.1016/j.intermet.2018.01.009

[17] Erdely P, Staron P, Maawad E, Schell N, Clemens H, Mayer S. Lattice and phase strain evolution during tensile loading of an intermetallic, multi-phase γ-TiAl based alloy. Acta Materialia. 2018;**158**:193-205. DOI: 10.1016/j.actamat.2018.07.062

[18] Li W, Liu J, Zhou Y, Li S, Wen S, Wei Q, et al. Effect of laser scanning speed on a Ti-45Al-2Cr-5Nb alloy processed by selective laser melting: Microstructure, phase and mechanical properties. Journal of Alloys and Compounds. 2016;**688**:626-636. DOI: 10.1016/j.jallcom.2016.07.206

[19] Ren GD, Dai CR, Mei W, Sun J, Lu S, Vitos L. Formation and temporal evolution of modulated structure in high Nb-containing lamellar γ-TiAl alloy. Acta Materialia. 2019;**165**:215-227. DOI: 10.1016/j.actamat.2018.11.041

[20] Akhlaghi M, Tayebifard SA, Salahi E, Asl MS. Spark plasma sintering of TiAl–Ti3AlC2 composite. Ceramics International. 2018;**44**(17):21759-21764. DOI: 10.1016/j.ceramint.2018.08.272

[21] Bakan E, Mauer G, Sohn YJ, Schwedt A, Rackel MW, Riedlberger F, et al. Cold gas spraying of Ti-48Al-2Cr-2Nb intermetallic for jet engine applications. Surface and Coatings Technology. 2018. In Press. DOI: 10.1016/j.surfcoat.2018.11.092

[22] Baudana G, Biamino S, Klöden B, Kirchner A, Weißgärber T, Kieback B, et al. Electron beam melting of Ti-48Al-2Nb-0.7 Cr-0.3 Si: Feasibility investigation. Intermetallics. 2016;**73**:43-49. DOI: 10.1016/j.intermet.2016.03.001

[23] Kastenhuber M, Rashkova B, Clemens H, Mayer S. Effect of microstructural instability on the creep resistance of an advanced intermetallic γ-TiAl based alloy. Intermetallics. 2017;**80**:1-9. DOI: 10.1016/j.intermet.2016.09.007

[24] Dahar MS, Tamirisakandala SA, Lewandowski JJ. Fatigue crack growth and fracture behavior of as-cast Ti-43.5 Al-4Nb-1Mo-0.1 B (TNM) compared to Ti-48Al-2Nb-2Cr (4822). Intermetallics. 2017;**91**:158-168. DOI: 10.1016/j.intermet.2017.08.015

[25] Mohammad A, Alahmari AM, Mohammed MK, Renganayagalu RK, Moiduddin K. Effect of energy input on microstructure and mechanical properties of titanium aluminide alloy fabricated by the additive manufacturing process of electron beam melting. Materials. 2017;**10**(2):211. DOI: 10.3390/ma10020211

[26] Tang HP, Yang GY, Jia WP, He WW, Lu SL, Qian M. Additive manufacturing of a high niobium-containing titanium aluminide alloy by selective electron beam melting. Materials Science and Engineering A. 2015;**636**:103-107. DOI: 10.1016/j.msea.2015.03.079

[27] Dahar MS, Tamirisakandala SA, Lewandowski JJ. Evolution of fatigue crack growth and fracture behavior in gamma titanium aluminide Ti-43.5 Al-4Nb-1Mo-0.1 B (TNM) forgings. International Journal of Fatigue. 2018;**111**:54-69. DOI: 10.1016/j.ijfatigue.2018.01.026

[28] Kastenhuber M, Klein T, Rashkova B, Weißensteiner I, Clemens H, Mayer S. Phase transformations in a β-solidifying γ-TiAl based alloy during rapid solidification. Intermetallics. 2017;**91**:100-109. DOI: 10.1016/j.intermet.2017.08.017

[29] Fang H, Chen R, Chen X, Yang Y, Su Y, Ding H, et al. Effect of Ta element on microstructure formation and mechanical properties of high-Nb TiAl alloys. Intermetallics. 2019;**104**:43-51. DOI: 10.1016/j.intermet.2018.10.017

[30] Chen Y, Niu H, Kong F, Xiao S. Microstructure and fracture toughness of a β phase containing TiAl alloy. Intermetallics. 2011;**19**(10):1405-1410. DOI: 10.1016/j.intermet.2011.05.006

[31] Saboori A, Gallo D, Biamino S, Fino P, Lombardi M. An overview of additive manufacturing of titanium components by directed energy deposition: Microstructure and mechanical properties. Applied Sciences. 2017;**7**(9):883. DOI: 10.3390/app7090883

[32] Calignano F, Manfredi D, Ambrosio EP, Biamino S, Lombardi M, Atzeni E, et al. Overview on additive manufacturing technologies. Proceedings of the IEEE. 2017;**105**(4):593-612. DOI: 10.1109/JPROC.2016.2625098

[33] Hu Y, Ning F, Cong W, Li Y, Wang X, Wang H. Ultrasonic vibration-assisted laser engineering net shaping of ZrO2-Al2O3 bulk parts: Effects on crack suppression, microstructure, and mechanical properties. Ceramics International. 2018;**44**(3):2752-2760. DOI: 10.1016/j.ceramint.2017.11.013

[34] Onuike B, Heer B, Bandyopadhyay A. Additive manufacturing of Inconel 718—Copper alloy bimetallic structure using laser engineered net shaping (LENS™). Additive Manufacturing. 2018;**21**:133-140. DOI: 10.1016/j.addma.2018.02.007

[35] Yadollahi A, Shamsaei N. Additive manufacturing of fatigue resistant materials: Challenges and opportunities. International Journal of Fatigue. 2017;**98**:14-31. DOI: 10.1016/j.ijfatigue.2017.01.001

[36] Tofail SA, Koumoulos EP, Bandyopadhyay A, Bose S, O'Donoghue L, Charitidis C. Additive manufacturing: Scientific and technological challenges, market uptake and opportunities. Materials Today. 2018;**21**(1):22-37. DOI: 10.1016/j.mattod.2017.07.001

[37] Xu W, Lui EW, Pateras A, Qian M, Brandt M. In situ tailoring microstructure in additively manufactured Ti-6Al-4V for superior mechanical performance. Acta Materialia. 2017;**125**:390-400. DOI: 10.1016/j.actamat.2016.12.027

[38] Bourell D, Kruth JP, Leu M, Levy G, Rosen D, Beese AM, et al. Materials for additive manufacturing. CIRP Annals. 2017;**66**(2):659-681. DOI: 10.1016/j.cirp.2017.05.009

[39] Dutta B, Froes FS. The additive manufacturing (AM) of titanium alloys. Metal Powder Report. 2017;**72**(2):96-106. DOI: 10.1016/j.mprp.2016.12.062

[40] Yan S, Wu D, Huang Y, Liu N, Zhang Y, Niu F, et al. C fiber toughening Al_2O_3-ZrO_2 eutectic via ultrasonic-assisted directed laser deposition. Materials Letters. 2019;**235**:228-231. DOI: 10.1016/j.matlet.2018.10.047

[41] Todai M, Nakano T, Liu T, Yasuda HY, Hagihara K, Cho K, et al. Effect of building direction on the microstructure

and tensile properties of Ti-48Al-2Cr-2Nb alloy additively manufactured by electron beam melting. Additive Manufacturing. 2017;**13**:61-70. DOI: 10.1016/j.addma.2016.11.001

[42] Hooper PA. Melt pool temperature and cooling rates in laser powder bed fusion. Additive Manufacturing. 2018; **22**:548-559. DOI: 10.1016/j.addma.2018.05.032

[43] Attar H, Ehtemam-Haghighi S, Kent D, Dargusch MS. Recent developments and opportunities in additive manufacturing of titanium-based matrix composites: A review. International Journal of Machine Tools and Manufacture. 2018;**133**:85-102. DOI: 10.1016/j.ijmachtools.2018.06.003

[44] Santos LS, Gupta SK, Bruck HA. Simulation of buckling of internal features during selective laser sintering of metals. Additive Manufacturing. 2018;**23**:235-245. DOI: 10.1016/j.addma.2018.08.002

[45] Traxel KD, Bandyopadhyay A. Reactive-deposition-based additive manufacturing of Ti-Zr-BN composites. Additive Manufacturing. 2018;**24**: 353-363. DOI: 10.1016/j.addma.2018.10.005

[46] Zhu YY, Tang HB, Li Z, Xu C, He B. Solidification behavior and grain morphology of laser additive manufacturing titanium alloys. Journal of Alloys and Compounds. 2019;**777**: 712-716. DOI: 10.1016/j.jallcom.2018.11.055

[47] Li GC, Li J, Tian XJ, Cheng X, He B, Wang HM. Microstructure and properties of a novel titanium alloy Ti-6Al-2V-1.5 Mo-0.5 Zr-0.3 Si manufactured by laser additive manufacturing. Materials Science and Engineering A. 2017;**684**:233-238. DOI: 10.1016/j.msea.2016.11.084

[48] Mantri SA, Banerjee R. Microstructure and micro-texture evolution of additively manufactured β-Ti alloys. Additive Manufacturing. 2018;**23**:86-98. DOI: 10.1016/j.addma.2018.07.013

[49] Tang H, Tao W, Wang H, Song Y, Jian X, Yin L, et al. High-performance infrared emissivity of micro-arc oxidation coatings formed on titanium alloy for aerospace applications. International Journal of Applied Ceramic Technology. 2018;**15**(3): 579-591. DOI: 10.1111/ijac.12861

[50] Grove T, Denkena B, Maiß O, Krödel A, Schwab H, Kühn U. Cutting mechanism and surface integrity in milling of Ti-5553 processed by selective laser melting. Journal of Mechanical Science and Technology. 2018;**32**(10): 4883-4892. DOI: 10.1007/s12206-018-0936-8

[51] Ning F, Hu Y, Cong W. Microstructure and mechanical property of TiB reinforced Ti matrix composites fabricated by ultrasonic vibration-assisted laser engineered net shaping. Rapid Prototyping Journal. 2018;**25**(3):581-591. DOI: 10.1108/RPJ-05-2018-0118

[52] Uhlmann E, Kersting R, Klein TB, Cruz MF, Borille AV. Additive manufacturing of titanium alloy for aircraft components. Procedia CIRP. 2015;**35**:55-60. DOI: 10.1016/j.procir.2015.08.061

[53] Heer B, Bandyopadhyay A. Silica coated titanium using laser engineered net shaping for enhanced wear resistance. Additive Manufacturing. 2018;**23**:303-311. DOI: 10.1016/j.addma.2018.08.022

[54] Zhao X, Li S, Zhang M, Liu Y, Sercombe TB, Wang S, et al. Comparison of the microstructures and mechanical properties of Ti–6Al–4V fabricated by selective laser melting and electron beam melting. Materials & Design. 2016;**95**:21-31. DOI: 10.1016/j.matdes.2015.12.135

[55] Pouzet S, Peyre P, Gorny C, Castelnau O, Baudin T, Brisset F, et al. Additive layer manufacturing of titanium matrix composites using the direct metal deposition laser process. Materials Science and Engineering A. 2016;**677**:171-181. DOI: 10.1016/j.msea.2016.09.002

[56] Hoosain SE, Pityana SL, Tlotleng M, Legopeng T. A comparative study on laser processing of commercially available titanium aluminide (TI-48Al-2Cr-2Nb) and in-situ alloying of titanium aluminide. In: Proceedings of the 18th Annual International Rapid Product Development Association of South Africa (RAPDASA); 7–10 November 2017, Durban ICC, RAPDASA; South Africa 2017. DOI: hdl.handle.net/10204/9805

[57] Bünck M, Stoyanov T, Schievenbusch J, Michels H, Gußfeld A. Titanium aluminide casting technology development. JOM. 2017;**69**(12):2565-2570. DOI: 10.1007/s11837-017-2534-0

[58] Imayev RM, Imayev VM, Oehring M, Appel F. Alloy design concepts for refined gamma titanium aluminide based alloys. Intermetallics. 2007;**15**(4):451-460. DOI: 10.1016/j.intermet.2006.05.003

[59] Doubenskaia M, Domashenkov A, Smurov I, Petrovskiy P. Study of selective laser melting of intermetallic TiAl powder using integral analysis. International Journal of Machine Tools and Manufacture. 2018;**129**:1-4. DOI: 10.1016/j.ijmachtools.2018.02.003

[60] Catchpole-Smith S, Clare AT. In-situ synthesis of titanium aluminides by direct metal deposition. Journal of Materials Processing Technology. 2017;**239**:230-239. DOI: 10.1016/j.jmatprotec.2016.08.031

[61] Sharman AR, Hughes JI, Ridgway K. Characterisation of titanium aluminide components manufactured by laser metal deposition. Intermetallics. 2018;**93**:89-92. DOI: 10.1016/j.intermet.2017.11.013

[62] Gussone J, Garces G, Haubrich J, Stark A, Hagedorn YC, Schell N, et al. Microstructure stability of γ-TiAl produced by selective laser melting. Scripta Materialia. 2017;**130**:110-113. DOI: 10.1016/j.scriptamat.2016.11.028

[63] Kimme T, Seifert M. Laser surface cladding of titanium aluminides: Technology and engineering for the turbine blade repair. Laser Technik Journal. 2017;**14**(5):18-20. DOI: 10.1002/latj.201700026

[64] Bacos MP, Thomas M, Raviart JL, Morel A, Mercier S, Josso P. Influence of an oxidation protective coating upon hot corrosion and mechanical behaviour of Ti–48Al–2Cr–2Nb alloy. Intermetallics. 2011;**19**(8):1120-1129. DOI: 10.1016/j.intermet.2011.03.014

[65] Dilip JJ, Miyanaji H, Lassell A, Starr TL, Stucker B. A novel method to fabricate TiAl intermetallic alloy 3D parts using additive manufacturing. Defence Technology. 2017;**13**(2):72-76. DOI: 10.1016/j.dt.2016.08.001

[66] Murr LE, Gaytan SM, Ceylan A, Martinez E, Martinez JL, Hernandez DH, et al. Characterization of titanium aluminide alloy components fabricated by additive manufacturing using electron beam melting. Acta Materialia. 2010;**58**(5):1887-1894. DOI: 10.1016/j.actamat.2009.11.032

[67] Chen Y, Yue H, Wang X, Xiao S, Kong F, Cheng X, et al. Selective electron beam melting of TiAl alloy: Microstructure evolution, phase transformation and microhardness. Materials Characterization. 2018;**142**:584-592. DOI: 10.1016/j.matchar.2018.06.027

[68] Li W, Liu J, Wen S, Wei Q, Yan C, Shi Y. Crystal orientation, crystallographic texture and phase

evolution in the Ti–45Al–2Cr–5Nb alloy processed by selective laser melting. Materials Characterization. 2016;**113**: 125-133. DOI: 10.1016/j.matchar.2016.01.012

[69] Gussone J, Hagedorn YC, Gherekhloo H, Kasperovich G, Merzouk T, Hausmann J. Microstructure of γ-titanium aluminide processed by selective laser melting at elevated temperatures. Intermetallics. 2015;**66**: 133-140. DOI: 10.1016/j.intermet.2015.07.005

[70] Seifi M, Salem AA, Satko DP, Ackelid U, Semiatin SL, Lewandowski JJ. Effects of HIP on microstructural heterogeneity, defect distribution and mechanical properties of additively manufactured EBM Ti-48Al-2Cr-2Nb. Journal of Alloys and Compounds. 2017; **729**:1118-1135. DOI: 10.1016/j.jallcom.2017.09.163

[71] Yue H, Chen Y, Wang X, Kong F. Effect of beam current on microstructure, phase, grain characteristic and mechanical properties of Ti-47Al-2Cr-2Nb alloy fabricated by selective electron beam melting. Journal of Alloys and Compounds. 2018;**750**: 617-625. DOI: 10.1016/j.jallcom.2018.03.343

[72] Chen Y, Yue H, Wang X. Microstructure, texture and tensile property as a function of scanning speed of Ti-47Al-2Cr-2Nb alloy fabricated by selective electron beam melting. Materials Science and Engineering A. 2018;**713**:195-205. DOI: 10.1016/j.msea.2017.12.020

[73] Shi X, Ma S, Liu C, Wu Q. Parameter optimization for Ti-47Al-2Cr-2Nb in selective laser melting based on geometric characteristics of single scan tracks. Optics & Laser Technology. 2017;**90**:71-79. DOI: 10.1016/j.optlastec.2016.11.002

[74] Cong W, Ning F. A fundamental investigation on ultrasonic vibration-assisted laser engineered net shaping of stainless steel. International Journal of Machine Tools and Manufacture. 2017; **121**:61-69. DOI: 10.1016/j.ijmachtools.2017.04.008

[75] Toozandehjani M, Kamarudin N, Dashtizadeh Z, Lim EY, Gomes A, Gomes C. Conventional and advanced composites in aerospace industry: Technologies revisited. American Journal of Aerospace Engineering. 2018; **5**(1):9-15. DOI: 10.11648/j.ajae.20180501.12

[76] Klein T, Schachermayer M, Mendez-Martin F, Schöberl T, Rashkova B, Clemens H, et al. Carbon distribution in multi-phase γ-TiAl based alloys and its influence on mechanical properties and phase formation. Acta Materialia. 2015;**94**:205-213. DOI: 10.1016/j.actamat.2015.04.055

[77] Kenel C, Dasargyri G, Bauer T, Colella A, Spierings AB, Leinenbach C, et al. Selective laser melting of an oxide dispersion strengthened (ODS) γ-TiAl alloy towards production of complex structures. Materials & Design. 2017; **134**:81-90. DOI: 10.1016/j.matdes.2017.08.034

[78] Kablov EN, Nochovnaya NA, Panin PV, Alekseev EB, Novak AV. Study of the structure and properties of heat-resistant alloys based on titanium aluminides with gadolinium microadditives. Inorganic Materials: Applied Research. 2017;**8**(4):634-641. DOI: 10.1134/S2075113317040116

[79] Kartavykh AV, Asnis EA, Piskun NV, Statkevich II, Gorshenkov MV, Korotitskiy AV. Room-temperature tensile properties of float-zone processed β-stabilized γ-TiAl (Nb, Cr, Zr) intermetallic. Materials Letters. 2017;**188**:88-91. DOI: 10.1016/j.matlet.2016.10.103

[80] Sienkiewicz J, Kuroda S, Murakami H, Araki H, Giżyński M, Kurzydłowski KJ. Fabrication and oxidation resistance

of TiAl matrix coatings reinforced with silicide precipitates produced by heat treatment of warm sprayed coatings. Journal of Thermal Spray Technology. 2018;**27**(7):1165-1176. DOI: 10.1007/s11666-018-0751-x

[81] Juechter V, Franke MM, Merenda T, Stich A, Körner C, Singer RF. Additive manufacturing of Ti-45Al-4Nb-C by selective electron beam melting for automotive applications. Additive Manufacturing. 2018;**22**:118-126. DOI: 10.1016/j.addma.2018.05.008

[82] Wenjun G, Chao G, Feng L. Microstructures of components synthesized via electron beam selective melting using blended pre-alloyed powders of Ti6Al4V and Ti45Al7Nb. Rare Metal Materials and Engineering. 2015;**44**(11):2623-2627. DOI: 10.1016/S1875-5372(16)60006-1

[83] Liu H, Zhang X, Jiang Y, Zhou R. Microstructure and high temperature oxidation resistance of in-situ synthesized TiN/Ti3Al intermetallic composite coatings on Ti6Al4V alloy by laser cladding process. Journal of Alloys and Compounds. 2016;**670**:268-274. DOI: 10.1016/j.jallcom.2015.10.168

[84] Li W, Li M, Yang Y, Wei Q, Cai D, Liu J, et al. Enhanced compressive strength and tailored microstructure of selective laser melted Ti-46.5 Al-2.5 Cr-2Nb-0.5 Y alloy with different boron addition. Materials Science and Engineering A. 2018;**731**:209-219. DOI: 10.1016/j.msea.2018.06.042

[85] Bresler J, Neumeier S, Ziener M, Pyczak F, Göken M. The influence of niobium, tantalum and zirconium on the microstructure and creep strength of fully lamellar γ/α2 titanium aluminides. Materials Science and Engineering A. 2019;**744**:46-53. DOI: 10.1016/j.msea.2018.11.152

[86] Jiang H, Tian S, Guo W, Zhang G, Zeng S. Hot deformation behavior and deformation mechanism of two TiAl-Mo alloys during hot compression. Materials Science and Engineering A. 2018;**719**:104-111. DOI: 10.1016/j.msea.2018.01.133

[87] Carrullo JC, Falcón JC, Borrás VA. Influence of process parameters and initial microstructure on the oxidation resistance of Ti48Al2Cr2Nb coating obtained by laser metal deposition. Surface and Coatings Technology. 2019;**358**:114-124. DOI: 10.1016/j.surfcoat.2018.11.015

[88] Dai J, Zhang F, Wang A, Yu H, Chen C. Microstructure and properties of Ti-Al coating and Ti-Al-Si system coatings on Ti-6Al-4V fabricated by laser surface alloying. Surface and Coatings Technology. 2017;**309**:805-813. DOI: 10.1016/j.surfcoat.2016.10.082

[89] Maliutina IN, Si-Mohand H, Sijobert J, Bertrand P, Lazurenko DV, Bataev IA. Structure and oxidation behavior of γ-TiAl coating produced by laser cladding on titanium alloy. Surface and Coatings Technology. 2017;**319**:136-144. DOI: 10.1016/j.surfcoat.2017.04.008

[90] Zhang Y, Bandyopadhyay A. Direct fabrication of compositionally graded Ti-Al2O3 multi-material structures using laser engineered net shaping. Additive Manufacturing. 2018;**21**:104-111. DOI: 10.1016/j.addma.2018.03.001

[91] Majumdar JD, Rittinghaus SK, Wissenbach K, Höche D, Blawert C, Weisheit A. Direct laser cladding of the silicide dispersed titanium aluminide (Ti45Al5Nb0. 5Si) composites. Optics & Laser Technology. 2018;**106**:182-190. DOI: 10.1016/j.optlastec.2018.03.012

[92] Guangyu Y, Wenpeng J, Pei Z, Liang J, Nan L, Jian W, et al. Microstructures of as-fabricated and post heat treated Ti-47Al-2Nb-2Cr alloy produced by selective Electron beam melting (SEBM). Rare Metal Materials and Engineering. 2016;**45**(7):1683-1686. DOI: 10.1016/S1875-5372(16)30140-0

[93] Klein T, Holec D, Clemens H, Mayer S. Pathways of phase transformation in β-phase-stabilized σ/γ-TiAl alloys subjected to two-step heat treatments. Scripta Materialia. 2018;**149**:70-74. DOI: 10.1016/j.scriptamat.2018.02.009

[94] Qiang F, Kou H, Tang B, Song L, Li J. Effect of cooling rate on microstructure evolution of Ti-45Al-8.5 Nb-0.2 W-0.2 B-0.02 Y alloy during multi-step heat treatment. Materials Characterization. 2018;**145**:210-217. DOI: 10.1016/j.matchar.2018.08.031

[95] Rittinghaus SK, Hecht U, Werner V, Weisheit A. Heat treatment of laser metal deposited TiAl TNM alloy. Intermetallics. 2018;**95**:94-101. DOI: 10.1016/j.intermet.2018.02.002

[96] Li W, Liu J, Zhou Y, Wen S, Tan J, Li S, et al. Texture evolution, phase transformation mechanism and nanohardness of selective laser melted Ti-45Al-2Cr-5Nb alloy during multi-step heat treatment process. Intermetallics. 2017;**85**:130-138. DOI: 10.1016/j.intermet.2017.01.016

[97] Tebaldo V, Faga MG. Influence of the heat treatment on the microstructure and machinability of titanium aluminides produced by electron beam melting. Journal of Materials Processing Technology. 2017; **244**:289-303. DOI: 10.1016/j.jmatprotec.2017.01.037

[98] Zhao ET, Niu HZ, Zhang SZ, Feng L, Yang SY. Microstructural control and mechanical properties of a β-solidified γ-TiAl alloy Ti-46Al-2Nb-1.5V-1Mo-Y. Materials Science and Engineering A. 2017;**701**:1-6. DOI: 10.1016/j.msea.2017.06.065

[99] Fan J, Liu J, Tian S, Wu S, Wang S, Gao H, et al. Effect of solidification parameters on microstructural characteristics and mechanical properties of directionally solidified binary TiAl alloy. Journal of Alloys and Compounds. 2015;**650**:8-14. DOI: 10.1016/j.jallcom.2015.05.160

[100] Majumdar T, Eisenstein N, Frith JE, Cox SC, Birbilis N. Additive manufacturing of titanium alloys for Orthopedic applications: A materials science viewpoint. Advanced Engineering Materials. 2018;**20**: 1800172. DOI: 10.1002/adem.201800172