

Additive Manufacturing of Titanium Alloys-A Review

M.B. Kiran

Associate Professor,
Department of Mechanical Engineering,
School of Technology,
Pandit Deendayal Petroleum University,
Gandhinagar, Gujarat-382007- INDIA
Kiranm.bhaskar@gmail.com

Abstract

Many high-performance components having complicated geometrical features nowadays are made by 3D printing (AM). 3D printing is also known as additive manufacturing (AM). titanium alloys. Many high-performance components made out of titanium alloys are used in the manufacture of simple components to complicated turbine components such as turbine blades. The main reason for selecting titanium alloys in the manufacture of high-performance components because, they are very light, have good tensile strength, and excellent resistance to corrosion. Titanium alloys have the capability of maintaining their properties at elevated temperatures. This makes them suitable for the manufacture of components that operates at high temperatures. Many components in the aircraft industry are being made by using titanium alloys. An attempt has been made in this research work for exploring the types of titanium alloys, types of the additive manufacturing process, microstructure, properties, and applications of titanium alloys. This research paper not only attempts in presenting the current literature but also provides future directions. Thus, it is valuable for both academicians and practitioners who would like to pursue research in this field.

Keywords

Titanium alloys, 3D-printing, AM of titanium alloys, Additive manufacturing, High performing components

1.Introduction

Earlier, many of the aircraft components were made out of aluminum and other alloys. These alloys though were not too heavy, but still used to have considerable weight and consume more fuel and energy. Also, the corrosion resistance of these alloys was not great. Especially at very high temperatures. There was a huge need from aerospace and space applications for the invention of new materials, with very high specific strength as well as material with excellent corrosion resistance. Especially at very high temperatures. Similarly, even in many chemical industries, there was a requirement for a new material with very good corrosion resistance. This was required for storing or handling different types of chemicals. Similarly, in the health care industry, there was a huge demand for the invention of new materials for making surgical instruments and medical implants. Here again, the requirement was good corrosion resistance and lightness. There was a huge demand from space industries for the invention of very light materials. There was also a need for the invention of a new manufacturing process that can achieve the dual objectives- capable of handling complex geometry and lightweight production. Also, there were huge requirements from the manufacturers of high-performing components for the invention of new materials with high strength, less weight as well as good corrosion resistance at elevated temperatures. This has made researchers started working for the invention of new materials with high specific strength as well as excellent corrosion resistance. In this context, titanium alloys came into being.

Titanium alloys are both strong and light and that is why they are being used in the manufacture of aerospace components. Today many medical implants used in the health care industry are being made by using titanium alloys. Whenever performance is the criteria for component, titanium alloy is preferred over others (Gungor et al., 2007, Froes, 2013, Imam et al. 2010, Froes et al., 2000). Even the blades of turbines are manufactured by using titanium alloys (Boyer et al. 1994, Froes et al. 1996), as these alloys not only have good strength but they are light by weight as well. Additionally, these alloys have very high corrosion resistance. There is a need by many practitioners to know the details of AM of titanium alloys and future directions. In this scenario, the present study assumes special significance.

2. Research methodology

Current work not only an attempt to study the existing literature on titanium alloys but an effort is also made to present research challenges and future directions. The findings from the current research work about the additive manufacturing of titanium alloys will help not only academicians but also practicing engineers interested in further research.

2.1 Titanium alloys classification

Titanium exists in two forms- α -type (above 883 °C) and β -type (below 883 °C). The phase change from α -phase to β phase will take place at transit temperature. In these alloys, alloying elements may exist either in α -phase or in β phase. Table 1 shows the alloying elements of titanium (for stabilizing α -phase).

Table 1 Elements added to form titanium alloy(α)

Alloying element	Symbol
Aluminium	Al
Gallium	Ga
Nitrogen	N
Oxygen	O

Table 2 Elements added to form titanium alloy(β)

Alloying element	Symbol
Molybdenum	Mo
Vanadium	V
Tungsten	W
Tantalum	Ta
Silicon	Si

The hexagonal closest packing crystal lattice is found in titanium alloys of alpha type. Aluminum will be added mostly as an alloying element for making titanium alloys of alpha type. When these alloys exist β -type, they will have a cubic body-centered (CBC) arrangement. Malinauskas et al. (2014) have tried to classify the titanium alloys. Table 2 shows the alloying elements of titanium (for stabilizing α -phase).

Pure titanium with very small amounts of alloying elements consists of grains in α and β spheroids. Sometimes iron is also added as an alloying element. When iron is added to the titanium alloy, it will make the alloy stable. The main problem here is that the mechanical strength of these alloys is very less. But an important feature of these alloys is that they have excellent resistance to corrosion.

The resistance to corrosion of these alloys may be improved by adding molybdenum. Sometimes palladium and nickel are also added for improving the corrosion resistance. It was observed that adding a small amount (0.18% to 0.4%) of oxygen strength will improve. Chemical industries largely use these alloys for the construction of containers for storing/or handling chemicals. These alloys are increasingly used in shipbuilding industries, as these alloys have good corrosion resistance. Aerospace industries also use titanium alloys for the manufacture of different aircraft components. Gas compressors manufacturing companies make use of titanium alloys. Desalination equipment is largely made of titanium alloys.

2.1.1 Titanium α -near α alloys.

Titanium α -near α alloys contain entirely of the alpha phase. These alloys will have Aluminium as an alloying element. The important characteristic of these alloys is that they exhibit moderate strength even at elevated temperatures. These alloys also have very high fracture toughness. These alloys also have very good creep resistance. These alloys, because of the availability of the β phase, good forge ability in the hot state. These alloys are used in sub-zero temperature applications. Turbine blades are increasingly made by using these alloys.

2.1.2 Titanium alpha and near beta alloys

Beta stabilizers of 4-6% are added to Titanium alpha and near beta alloys. Titanium (α) and (near α) alloys will have better creep resistance than these alloys. β phase elements, in these alloys, will govern the quantity of β phase particles. On account of aging, when β phase particles transform into α -phase particles, there will be enhanced tensile strength of these alloys. In the meantime, there will be a reduction in ductility as well. These alloys are being used in applications that require high fatigue strength. These alloys also exhibit excellent creep resistance.

2.1.3 Titanium beta alloys.

Large amounts of β phase elements are found in titanium beta alloys. These alloys exhibit very good tensile strength. An important feature of these alloys is that these alloys may be subjected to heat treatment. What was observed is that even post-heat treatment, these alloys exhibit very low ductility. These alloys cannot be deployed in functions that require high fatigue strength. Literature reported that titanium (β)-alloys are used for making aircraft engines, which operate at 510°C. It was reported that these alloys may contain 10% chromium. When these alloys are subjected to heat treatment, they become strong and also exhibit high formability. Fasteners are normally made by using these alloys. Many components in air-craft which operate at elevated temperatures are normally made by these titanium beta alloys.

2.1.4 Titanium alloys and designations:

Titanium alloys with 5% of Aluminium as well as 2.5% of tin become Ti-5Al-2.5Sn alloy. Many alloy designation systems exist. For example, ASTM (Liu et.al. 2017) is one such alloy designation system. Different grades of titanium alloys are available in the market. When a particular application requires soft and ductile material, Grade 1 titanium alloys find applicable. One important feature of these alloys is that they have excellent corrosion resistance. These alloys can be formed in cold conditions. Similarly, Grade 2 alloys will have better tensile strength as well as yield strength than Grade 1 type alloys. So, as the grade number of these alloys increases, tensile strength increases. The same is true about yield strength. These alloys are used increasingly in fabrication applications.

2.2 Additive Manufacturing (AM) Process

2.2.1 -Laser Beam Melting (LBM)

In the LBM process, heat energy required for melting, evenly spread metal powder (on a metallic platform-50 mm X 50 mm), is obtained from laser light, having a wavelength of 1060 nm.

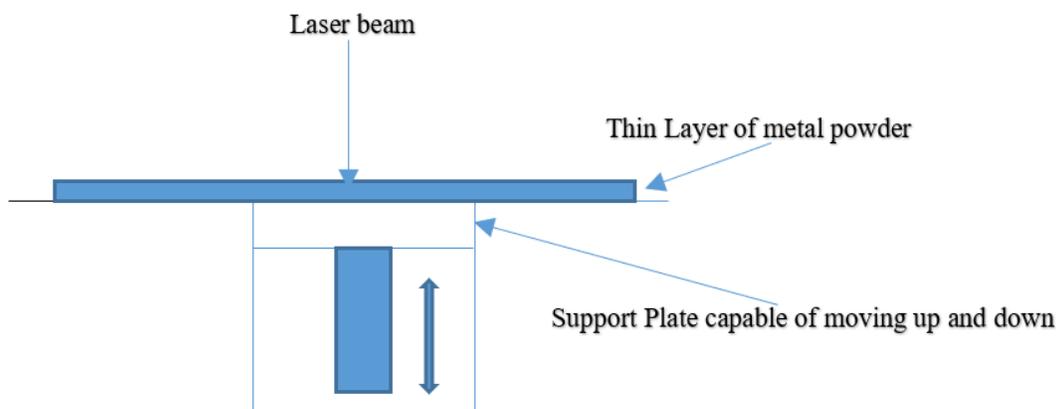


Figure 1 Principle of Laser beam melting

The layer thickness of the evenly spread metal powder is about 50-100 micrometers. For evenly distributing metal powder, a leveling system is used. The laser beam used in this set-up uses 20 Watts to 1 KW. The size of the laser beam is around 50 micrometers. Evenly spread metal powder will be scanned by using a laser at a speed of 15 m/s. When laser light moves over the metal powder, it will melt the powder. Molten metal will fuse with the layer already solidified.

Once the solidification is over, the build plate is brought down. The entire process is repeated till the final product is made. To protect the molten metal from oxidation, the entire process is performed in a closed chamber. The chamber also contains an inert gas, viz. Argon or Nitrogen. Figure 1 depicts the principle of LBM. Many researchers have worked on LBM (Tan et al., 2016, Dai et al., 2016, Zhao et al., 2016). LBM has the advantage of no moving parts and hence 3D objects having intricate profiles can be made by this process.

2.2.2 -Electron Beam Melting (EBM)

In EBM, electron ray (focused by electron lenses) made faster by using 60 kV, is used as the source of energy (700° C) for liquifying evenly spread metal particles (on a metallic platform-50 mm X 50 mm), is obtained from an electron beam, having a wavelength of 1060 nm. The layer thickness of the evenly spread metal powder is about 50-200 micrometers. For evenly distributing metal powder, a leveling system is used. The electron beam uses about 30 mA of beam current. The size of the electron beam is around 50 micrometers.

Evenly spread metal powder will be scanned by using an electron beam at a speed of 104 mm/s. When laser light moves over the metal powder, it will melt the powder. Molten metal will fuse with the layer already solidified. Once the solidification is over, the build plate is brought down. The entire process is repeated till the final product is made. To shield the molten metal from oxidation, the entire process is performed in a closed chamber. The chamber is also filled with a vacuum- lower than 10-2 Pa. Figure 2 shows the principle behind the process. Many researchers have worked on EBM (Appolaire et al. 2005, Dai et al. 2017, Dai et al. 2016, Chen et al. 2017).

For electron beam melting to be successful, certain challenges need to be addressed. During the planning stage, the designers will have to study the geometry of the part, overhang requirements, component inclination, the surface finish requirements, tolerance requirements, post-processing requirements. Similarly, once a product is made by additive manufacturing (Electron beam melting process) it requires proper post-processing, such as loose powder should be removed by sandblasting process. Additive manufactured products will have very high residual stresses, thus a component made by additive manufacturing requires proper heat requirement. Normally used heat treatments include vacuum heat treatment process, hot isostatic pressing, etc.

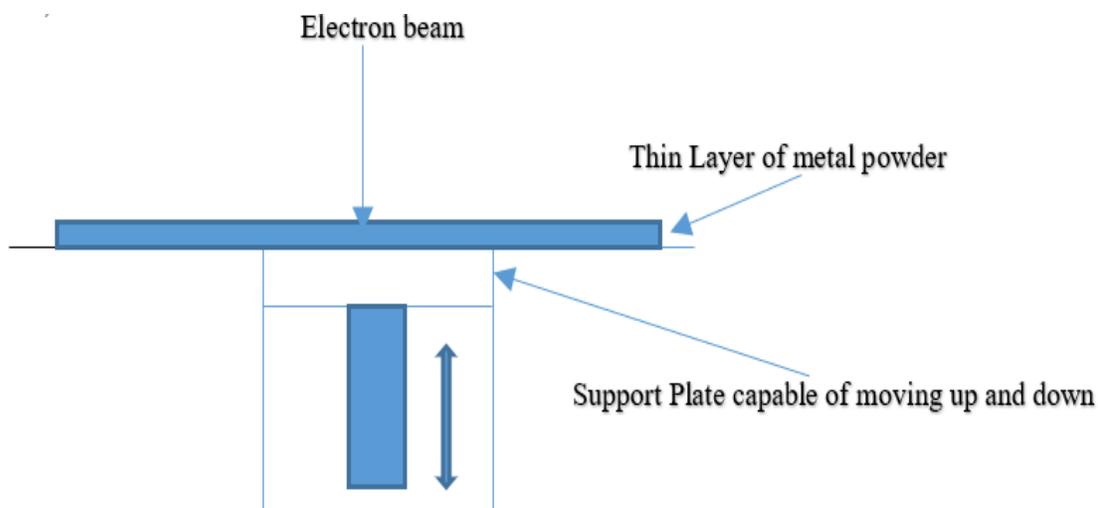


Figure 2 Principle of EBM

2.2.3 Laser Metal Deposition (LMD)

Figure 3 shows the principle behind the process. In the LMD process, metal powder is fed using a special type of nozzle. CO₂ laser supplies the necessary heat for liquifying metal powder. CO₂ laser enters the nozzle from the center. As and when it comes in contact with the metal powder, it will melt the metal powder. Also, Argon / Helium gas is used for protecting the molten metal from oxidation. The important characteristic of the process is that higher build rates are possible. Researchers have also reported that larger build volumes are possible. Many researchers have been working on LMD (Zhang et al. 2011, Murr et al. 2010, Grotowski et al. 2010, Bai et al. 2017). LMD process finds application in the repair of damaged products. The difference between LMD and LBM is the metal particles that are liquified by using a laser beam are directly deposited in the production of a 3D object. Thus, wastage of metal powder is minimum in the case of the laser metal deposition process. The similarity between the LBM and LMD is that both processes use a laser beam as an energy source. The main disadvantage of LMD is that the process cannot be used in the manufacture of intricate profiles. For manufacturing intricate profiles, LBM is preferred. Higher metal deposition rates are possible in the LMD process.

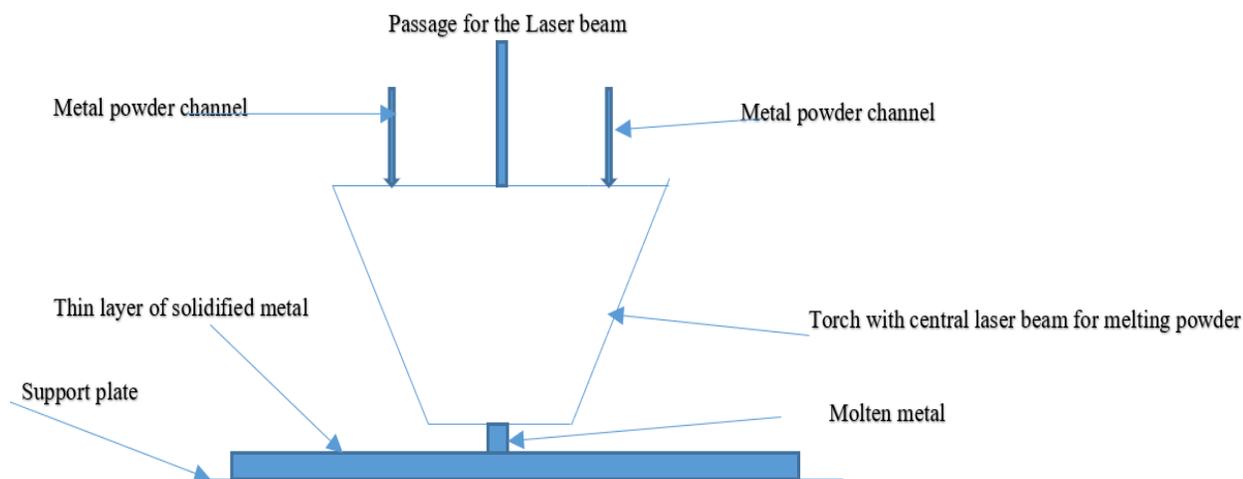


Figure 3 Principle of Laser metal deposition

The biggest challenges in additive manufacturing are high consumption of electric power during additive manufacturing, reducing the waste concerning supporting plates, manufacturing defects identification, optimizing the process parameters, improving mechanical properties of additive manufactured products, improving the surface finish of additive manufactured products, health hazards.

It is reported in the literature that while manufacturing products by additive manufacturing process emit billions of harmful particles every minute. These are harmful to human beings, Additive manufactured products are very expensive, Products do not have high density when compared to machined products.

3. Microstructure and properties

3.1 Laser Beam Melting (LBM)- Microstructure and properties

Scan speed will determine the microstructure of AM-made titanium alloys (Attar et al. 1941). Coarse grain structure will be formed by using machining parameters, speed: 100 mm/s; power: 90W. The coarse-grained microstructure is formed because of the conversion of the β phase into α phase while cooling, Researchers have observed the creation of the martensitic α phase when the speed of scanning exceeds 200 mm/s. Rapid cooling during additive manufacturing would result in large thermal gradients and hence there will be high residual stresses in additive manufactured products. Manufacturing defects during additive manufacturing would result in reduced strength of additive manufactured products.

3.2 Microstructure and properties of Electron Beam Melting (EBM)

A product made by electron beam melting is made up of β grains (Zhang et al. 2016) with properly marked grain boundaries and α/β --microstructure. Researchers have observed microstructures obtained by the EBM process were different from the microstructure obtained by the SLM process. During the SLM process, high cooling rates are possible and this would result in the transformation of β to α martensite.

The reliable performance of EBM produced component largely depends upon the reliability of mechanical properties. These are largely controlled by EBM product microstructure. The EBM process is unique in that they have micro melting zones. These micro-melting zones will control the mechanical properties of the product. Thus, to achieve reliability in mechanical properties, there is a need to have complete control over the micro melting zone and the entire process. Researchers have observed certain properties *viz.* UTS and elongation properties are more stable and also highly reliable.

Researchers have observed that β grains thickness is directly proportional to the constructing height of the part. This happens because of slow cooling rates. Tan et.al (2016) has done a detailed investigation into the EBM process. They have noticed that the microstructure of the last layer was different from the microstructure of the first layer even in a given sample. They have noticed that the strength of the component increases with a reduced lamellae thickness. It was also noticed that the increase in grain size has resulted in a reduction in lamellae thickness. Reduction lamellae thickness has increased the tensile strength of the component. EBM produced product when heated above β transit temperature produces a structure normally obtained from annealing treatment. Researchers have noticed that EBM made component has more tensile strength than a component produced from forging.

Zhao et.al (2016) have studied EBM-made components and found that the tensile strength of the component depends upon the component diameter. They concluded that as the diameter of the component size increases the tensile strength reduces. It was also found that as the diameter increases, the tensile strength also increases. EBM produced component exhibits a unique microstructure containing different phases. It was found by many researchers that α -phase with HCP structure will have less corrosion strength. On the other hand, EBM products with a microstructure containing β -phase with BCC structure will have better resistance to corrosion (Chen et al. 2017, Dai et al. 2016). In EBM manufactured products, the alpha phase starts growing over the prevailing β grains. Appolaire et al. (2005) noticed when the cooling rate increases the size of β & α particles decreases.

Titanium alloys have better corrosion resistance when examined against the wrought components. Bai et al. (2017) have reasoned that this was because not only due to the β phase but also due to refined α/β phases. Products manufactured by AM are found to contain porous structures. They also have good properties. Titanium alloys are applied in the health care domain (Murr et al. 2010, Zhang et al. 2011, Attar et al. 1941, Grotowski et al. 2010). Thijs et al. (2010), as well as Zhang et al. (2016), have observed that microstructures of EBM and SLM products are different. Heat treatment is performed on AM manufactured products for improving the mechanical properties. Additive manufactured products will have defects that are explained in the following paragraphs.

Improper selection of process parameters would result in the porous structure. As discussed in the last paragraph, they are used in medical implants. However, in certain applications, detrimental effects are observed. The ductility of AM manufactured products would depend on the pore shape and also its orientation (Vilaro et al. 2011). It was also noticed that these pores would act as starting points for crack propagation (Biswas et al. 2012). Pore size may be as big as 300 micrometers. Even the location of these pores, size of the pores, the orientation of the pores is influenced by the selection of the thickness of the layer. Researchers have demonstrated that by selecting proper process variables such as the thickness of the lamellae and speed of scanning these defects can be minimized.

Lack of fusion is a type of defect that was mainly formed due to the usage of insufficient energy during AM fabrication. These defects may lead to the fatigue failure of AM manufactured products. Keyhole collapse is a type of defect that was mainly formed due to the usage of excess energy during AM fabrication. Balling defect is mainly due to the lack of dampening of solid particles. Rough surface generation is mainly due to layer-by-layer formation and using metallic powder during AM process.

3.3 Microstructure -properties-of Laser Metal Deposition

The Microstructure of typical LMD processed $\alpha + \beta$ titanium alloys may exhibit structures such as - Widmanstätten structure: Primary alloy is made up of β grains. α grains are found in the boundaries. These alloys have very low ductility. They have a good fatigue strength, Duplex microstructure: In this case, α particles are distributed in the β matrix. These alloys have high mechanical properties, Basket-weave microstructure: The microstructure predominantly consists of α particles. They exhibit very high ductility, Equiaxed structure: Here both α and β grains are in a polygonal shape, By suitable heat treatment of AM made titanium alloys desired mechanical properties can be achieved.

Many researchers (Zhao, 2017, Van Arkel et al. 2015, Morita et al. 2005, Mardaras et al. 2017, Leyens et al., 2003) have worked on improving the mechanical properties such as increased ductility by using solution heat treatment and aging. It was also demonstrated that the mechanical properties largely depend upon the microstructure. The temperature range used during solution treatment is from 400C -1000C lower than β transus temperature. Ductility may be increased by subjecting the titanium alloy to stress relief annealing. This treatment will produce coarser α grains.

It was reported in the literature that the type of cooling will determine the tensile properties. After proper heat treatment, we may expect increased tensile strength to ductility balance may be maintained. Currently in LMD deposition rates of the order of 0.5 kg/hr. The deposition rates require improvement for enhancing the productivity of the process. Much research is required in the area of local shielding while performing LMD. This can significantly bring down the cost of manufacturing. Researchers have observed that AM-made products are found to have mechanical strengths comparable to that of products made by conventional manufacturing processes. It was also found that the static strength, as well as fatigue strengths, entirely depends upon the microstructure of AM-produced product.

4. Applications

4.1 Medical applications

AM-made titanium alloys are commonly used in the healthcare domain. Titanium alloys are being used for treating bone fractures. These alloys have less stiffness. These alloys have good corrosion resistance as well as a very good machinability index. Researchers have observed that titanium alloys had a higher Young's modulus (113 GPa) than bone (15-20 GPa). Commercially pure titanium (CPTi, ASTM F67) is mainly used in the dental application (Zhang et al. 2012). Many researchers (Hakimi et al. 2010; Esparragoza-Cabrera et al. 2009) have reported successful titanium alloy implants. Titanium alloy implants have a lower stress protecting effect when compared with stainless steel implants (Roderer et al. 2014).

4.2 Aerospace applications

There is much opportunity for the invention of new materials /alloys in the aerospace industries. This is because materials /alloys which are light and strong can cause significant savings in energy savings, especially in the aerospace industry. This is because when the weight of aircraft/ spacecraft reduces, it will require less fuel and this, in turn, will result in significant energy savings. Earlier hydraulic tubes were made of steel. But nowadays, with the availability of titanium alloys, hydraulic tubes are largely made from titanium alloys. Materials with a high strength and low weight are also in huge demand in the space industry as well. This has made researchers work on new inventions of new titanium alloys for aerospace applications. Many research works have reported the use of titanium alloy material in several aerospace applications. Titanium alloy enjoys advantages (Peters et al. 2003) such as -weight reduction, high application temperature, corrosion resistance, and space limitations. Aircraft engine consists of 36% of materials made up of Titanium alloys (Peters et al. 2003). These alloys are also used to prevent crack propagation in aircraft bodies. The aircraft floor (including kitchen and toilet floor) is made up of pure titanium alloys because this area requires maximum corrosion resistance.

Prolonged exposure of α - titanium alloys to high temperature would form α -case. This mainly due to the oxygen enrichment. This would result in the reduction of ductility as well as fatigue strength. One of the limitations of titanium alloys is that they cannot be used in the manufacture of disks and blades used in the last stage of a compressor. As these parts will be operating at very high temperatures. As titanium alloys tend oxidation. Because of these reasons these components of a compressor are made out of Nickel-based alloys. Though Nickel-based alloys are roughly twice as heavy as titanium alloys.

Cast titanium alloys (Ti- 47Al-2Cr-2Nb) are used in the manufacture of low-pressure turbine blades of jet engines. This would not only reduce the weight of the entire engine but also results in a reduced centrifugal force on the disk. Titanium matrix composites (TMC) have high stiffness and good strength at high temperatures.

Table 1 Properties of titanium alloys

α alloys	Alloy-grades	Tensile strength	Remarks
	Grade-I	500 MPa	Good formability; commonly found in the deep drawing operation
	Grade-II	450 MPa	
	Grade-III	Higher-strength	Manufacture of pressure vessel fabrication
	Grade IV	Strength, as high as 740 MPa	Manufacture of the pressure vessel. Also used in fabrication by welding
Near α - Alloys:		Good creep resistance High tensile strength	These alloys are best suited for high-temperature applications.
α and β alloys:			Used in the aircraft industry.

These alloys are also employed in the making of aircraft toilet floors, where there is a very high probability of corrosion is being made by using titanium alloys. Titanium alloys are also employed in the construction of cockpit windows, as they are highly vulnerable to bird strikes during flight. These air-craft windows are made of titanium alloys by using forging operation. Military aircraft normally demand higher thermal load as well as mechanical strength. This necessitates the employment of these alloys in the manufacture of components in military air crafts. Earlier tail assembly of an aircraft was made by using aluminum alloys. Nowadays, the tail assembly of an aircraft is normally made by using titanium alloys, as these alloys have a fairly good coefficient of thermal expansion. These alloys are deployed in the construction of aircraft springs. The main advantage of titanium beta alloys is that they are very light and there will be significant savings concerning weight. Many of the jet engine blades are being made by using titanium alloys. Titanium aluminide alloys have an orderly structure and high resistance to creep and again finds application in aerospace industries. Rotor heads of helicopters are also being made out of titanium alloys.

4.3 Chemical industry

Though titanium alloys have excellent resistance to corrosion in normal usage. The resistance to corrosion is mainly because of the shielding oxide cover. Oxide cover is developed when titanium is heated to 450⁰C-800⁰C in the air from 2 to 10 minutes (Schutz et al. 1997). These oxide layers provide corrosion resistance to titanium as long as the oxide layer exists. This oxide layer may be damaged because of impact or surface wear or plastic deformation. They however have poor wear resistance in special conditions. Such as when they are exposed to chloride solutions and other chemical environments.

5. Conclusion

Additive manufacturing is helpful in manufacturing products having complicated geometry. Additive manufacturing consumes more energy than conventional manufacturing processes. This is one area that requires further research. Researchers may devise a new scheme for making it more energy-efficient and cost-effective. There is much scope for quality inspection of additive manufactured products. Much research is required in identifying the different types of defects in additive manufactured products. With the advent of Industry 4.0, machine-to-machine communication is possible. Thus, defect data can be shared so that timely actions are possible. Changing the process parameters in auto mode by looking into defect data can be one such example. Protecting the cyber-physical system from cyber-attacks is another active area for research.

Assessing and evaluating the necessary security infrastructure is the biggest challenge being faced by many companies operating using Industry 4.0 technologies. Researchers may address challenges such as reducing consumption of electric power during additive manufacturing, reducing the waste concerning supporting plates, manufacturing defects identification, optimizing the process parameters of AM process, improving mechanical properties of additive manufactured products, improving the surface finish of additive manufactured products, reducing health hazards – It is reported in the literature that while manufacturing products by additive manufacturing process emit billions of harmful particles every minute. These are harmful to human beings, additive manufactured products are very expensive, products do not have high density when compared to machined products.

Scan speed will determine the microstructure of AM-made titanium alloys. Coarse grain structure will be formed by using machining parameters, speed: 100 mm/s; power: 90W. The coarse-grained microstructure is formed from the conversion of the β phase into the α phase while cooling, Researchers have observed the creation of the martensitic α phase when the speed of scanning exceeds 200 mm/s. Rapid cooling during additive manufacturing would result in large thermal gradients and hence there will be high residual stresses in additive manufactured products. Manufacturing defects during additive manufacturing would result in reduced strength of additive manufactured products. This clearly shows that there is a huge demand to create defect-free AM products. This is one area that requires further research. Though many researchers have been working on understanding the correlation between microstructure on one hand and properties of additively manufactured titanium alloys on the other hand. Much research is required especially in analyzing the microstructure so that required mechanical properties may be achieved. This would help in extending the scope of titanium alloys.

Current research has identified the extensive application of additive manufactured titanium alloys in the area such as –Bio-medical applications: Literature has reported many successful dental implants using additively manufactured titanium alloys. The usefulness of Titanium alloys may be explored in new areas of biomedical applications. Researchers can also explore the fabrication of products more economically, Aerospace industries: Many research works have reported the use of Ti-6Al-4V material in several aerospace applications. There is significant scope for the reduction of the cost of manufacturing titanium products. Much research is required to be done in the area of manufacturing cost reduction in additive manufacturing of titanium alloys.

Titanium alloy enjoys the advantages, such as weight reduction, high application temperature, corrosion resistance, space limitations. Chemical industries: Though titanium alloys have excellent resistance to corrosion in normal usage. The resistance to corrosion is mainly from the shielding oxide cover. Oxide cover is developed when titanium is heated to 450^oC-800^oC in the air from 2 to 10 minutes. These oxide layers provide corrosion resistance to titanium as long as the oxide layer exists. This property of titanium alloys may be explored in the manufacturing of products such as (i) coating in pipes carrying chemicals (ii) Design of material handling devices (iii) Pharma companies for storing tablets and other tablets.

Titanium α can be subjected to heat treatment in the hot state. They are also easily forged in a hot state due to the availability of the β phase. They are also weldable very easily. Turbine blades are made by AM using titanium alloys. Titanium alloys are also increasingly find's the application in products requiring high pressure and sub-zero temperatures. In the future, it is expected that titanium alloys may be used in the fabrication of products. Titanium beta alloys exhibit high tensile strength. They are also easily formable. Properties of alloys can be improved by subjecting to heat treatment. Fasteners are normally made of these alloys. Aircraft components are usually made of these alloys. Titanium alloys have very good heat resistance and they find application in air-craft engine components. Landing gears used in air-craft are also made from titanium alloys. This is because of their high corrosion resistance properties. Though many products are being made by using these alloys, still there is much scope for the use of titanium alloys in product manufacturing in agriculture, shipbuilding, and other fields.

Presently, applications of additive manufactured titanium alloys are very limited to certain areas such as bio-medical, aerospace, and chemical industries. There is much scope of titanium alloys in other areas such as agriculture, pharmaceutical, shipbuilding, space research, transportation steel manufacturing, and others.

Acknowledgments

The author would like to express his sincere thanks to the management of Pandit Deendayal Petroleum University, for providing the necessary infrastructure and timely support.

References

- Amirhossein Goharian, and Mohamed R. Abdullah, in *Trauma Plating Systems, Biomechanical, Material, Biological, and Clinical Aspects*, pp. 115-142, 2017
- Aprilaire, B., Hericher, L., and Aeby-Gautier, E., Microstructural formation in Ti alloys: In-situ characterization of phase transformation kinetics, *Acta Materialia*, vol.53 (10), pp.3001-3011,2005.
- Attar, H., Bönisch, M., Calin, and M. et al. Comparative study of microstructures and mechanical properties of in situ Ti–TiB composites produced by selective laser melting, powder metallurgy, and casting technologies. *Journal of Materials Research*, vol.29, pp. 1941–1950 (2014).
- Biswas, N., Ding, J.L., Balla, V.K., and Field, D.P., Bandyopadhyay, A., Deformation, and fracture behavior of laser processed dense and porous Ti6Al4V alloy under static and dynamic loading, *Materials Science and Engineering: A*, vol.549, pp.13-221, 2012.
- Boyer, R.R., Welsch, G., and Collings EW(Eds.), *Materials Properties Handbook: Titanium Alloys*, ASM Int., Materials Park, OH, 1994. ISBN: 978-0-87170-481-8
- Chen, Y., Zhang, J., Dai, N., Qin, P., Attar, H., and Zhang, L.C., the Corrosion behavior of selective laser melted Ti-TiB bio-composite in simulated body fluid, *Electrochimica Acta*, vol.232, pp.89-97, 2017.
- Dai, N., Zhang, L. C., Zhang, J., Chen, Q., and Wu, M., Corrosion Behavior of Selective Laser Melted Ti-6Al-4V Alloy in NaCl Solution, *Corrosion science*, vol.102, pp.484-489, 2016.
- Esparragoza-Cabrera L, et al. Open reduction and internal fixation of unstable dorsally displaced distal radius fractures using a fixed-angle volar plate with locking screws. *Rev Esp Cir Ortop Traumatol (English Ed)* 2009;53, (6):35763.
- Fousova, M, Vojtech, D, Doubrava, K, Daniel, M, and Lin, C.F., Influence of Inherent Surface and Internal Defects on Mechanical Properties of Additively Manufactured Ti6Al4V Alloy: Comparison between Selective Laser Melting and Electron Beam Melting. *Materials (Basel, Switzerland)* 2018;11.
- Froes, F. H., and Imam, M. A., Cost Affordable Developments in Titanium Technology and applications. *Key Engineering Materials*, vol.436, pp. 1–11, 2010. <https://doi.org/10.4028/www.scientific.net/kem.436.1>
- Froes, F.H., *Powder metallurgy of titanium alloys*, in Chang Isaac, Zhao Yuyuan (Eds.), *Advances in Powder Metallurgy*, Woodhead Publishing, Philadelphia, USA, pp. 202.2013.
- Froes, F.H., Te-Lin, Y., and Weidenger, H.G., Titanium, Zirconium, and Hafnium Chapter 8, in K.H. Matucha (Ed.), *Materials Science and Technology – Structure and Properties of Nonferrous Alloys*, vol. 2, VCH Weinheim, FRG, pp. 401,1996.
- Froes, F.H., *Titanium Alloys, chapter 8 of the Handbook of Advanced Materials*, Chief J.K. Weasel (Ed.), McGraw-Hill Inc., New York, NY, 2000.
- Gaytan, S., Murr, L., and Martinez, E. et al., Comparison of Microstructures and Mechanical Properties for Solid and Mesh Cobalt-Base Alloy Prototypes Fabricated by Electron Beam Melting. *Metallurgical and Materials Transactions A*, vol.41, pp.3216–3227 (2010).
- Goharian, A., and Abdullah, M. R., Bioinert Metals (Stainless Steel, Titanium, Cobalt-Chromium), *Trauma Plating Systems*, pp. 115–142, 2017. doi:10.1016/b978-0-12-804634-0.00007-0.
- Grotowski, V. J. F., Zhang, L. C., and Sercombe, T. B., Prototypes for Bone Implant Scaffolds Designed via Topology Optimization and Manufactured by Solid Freeform Fabrication, *Advanced Engineering Materials*, vol.12, pp.1106-1110.,2010.
- Gungor, M.N., Imam, M.A., and Froes F.H. (Eds.), *Innovations in Titanium Technology*, TMS, Warrendale, PA, 2007.
- Hakimi M, et al., Functional results and complications following locking palmar plating on the distal radius: a retrospective study. *Journal of Hand Surgery*, vol.35(4), pp. 283-288, 2010. <https://doi.org/10.1016/j.matdes.2019.108091>.
- Kuo CN, Chua C, Peng PC, Chen Y, Sing SL, and Sheng H, et al., Microstructure evolution and mechanical property response via 3D printing parameter development of Al–Sc alloy. *Virtual Physics Prototyping*, vol.15, pp.120–129,2020.

- Leyens, C.; and Peters, M., *Titanium and Titanium Alloys: Fundamentals and Applications*; Wiley-VCH: Weinheim, Germany; John Wiley: Chichester, UK, 2003.
- Liu, Y. J., Li, S. J., Wang, H. L., Hou, W. T., Hao, Y. L., Yang, R., Sercombe, T. B., and Zhang, L. C., Microstructure, defects and mechanical behavior of beta-type titanium porous structures manufactured by electron beam melting and selective laser melting, *Acta Materialia*, vol.113, pp.56-67,2016.
- Liu, Y. J., Wang, H. L., Li, S. J., Wang, S. G., Wang, W. J., Hou, W. T., Hao, Y. L., Yang, R., and Zhang, L. C., Compressive and fatigue behavior of beta-type titanium porous structures fabricated by electron beam melting, *Acta Materialia*, vol.126, pp.58-66, 2017.
- Peters, M., Kumpfert, J., Ward, C.H., Leyens, C., *Advanced Engineering Materials -Review Titanium Alloys for Aerospace applications*, vol.5, pp.419-427, 2003.
- Malinauskas, M., Rekštytė, S., Lukoševičius, L., Butkus, S., Balčiūnas, E., Pečiukaiytė, M., Baltriukienė, D., Bukelskienė, V., Butkevičius, A., Kucevičius, P., Rutkūnas, V., and Juodkasis, S., 3D Microporous Scaffolds Manufactured via Combination of Fused Filament Fabrication and Direct Laser Writing Ablation, *Micromachines 2014*, vol.5(4), pp.839-858, 2014. <https://doi.org/10.3390/mi5040839>
- Mardaras, J., Emile, P., and Santgerma, A., Airbus approach for F&DT stress justification of Additive Manufacturing parts. *Procedia Structural Integrity*, vol.7, pp.109–115, 2017.
- Morita, T., Hatsuoka, K., Iizuka, T., Kawasaki, K., and Strengthening of Ti–6Al–4V Alloy by Short-Time Duplex Heat Treatment., *Material Transactions*, vol.46, pp.1681–1686, 2005
- Niloofer Sanaei, Ali Fatemi, and Nam Phan, Defect characteristics and analysis of their variability in metal L-PBF additive manufacturing, *Materials & Design*, vol. 182, 2019,108091, ISSN 0264-1275,
- Pei-Xun Zhang, Feng Xue, Yu Dang, Tian-Bing Wang, Jian-Hai Chen, Hai-Lin Xu, Zhong-Guo Fu, Dian-Ying Zhang, and Bao-Guo Jiang, Clinical effect of distal radius fracture treated with open reduction and internal plate fixation, *Chinese Medical Journal*, vol.125(1), pp.140-143, 2012.
- Peters, M., Kumpfert, J., Ward, C.H., and Leyens, C., Review Titanium Alloys for Aerospace applications, *Advanced Engineering Materials*, vol.5, pp. 419-427, 2003.
- Puebla, K., Murr, L.E., Gaytan, S.M., Martinez, E., Medina, F., and Wicker, R.B., Effect of Melt Scan Rate on Microstructure and Macrostructure for Electron Beam Melting of Ti-6Al-4V, *Materials Sciences, and Applications*, vol.3(5), pp. 259-264,2012.
- Roderer G, et al. Delayed bone healing following high tibial osteotomy related to increased implant stiffness in locked plating. *Injury*, vol.45 (10),164852,2014.
- Sanaei, N, Fatemi, A, and Phan, N., Defect characteristics and analysis of their variability in metal L-PBF additive manufacturing. *Materials and Design*, 2019;182:108091. <https://doi.org/10.1016/j.matdes.2019.108091>
- Schutz, R.W., Gregory, J.K., Rack, H.J., and Eylon, D. (Eds.), Surface Performance of Titanium, *The Minerals, Metals and Materials Society*, pp. 1–22, 1997.
- Shui, X., Yamanaka, K., Mori, M., Nagata, Y., Kurita, K., and Chiba A. Effects of post-processing on cyclic fatigue response of a titanium alloy additively manufactured by electron beam melting., *Matter Science and Engineering, A*, vol.680, pp.239–48, 2017.
- Tan, X., Kok, Y., Toh, W. Q., Tan, Y. J., Descoins, M., Mangelinck, D., Tor, S. B., Leong, K. F., and Chua, C. K., Revealing martensitic transformation and α/β interface evolution in electron beam melting three-dimensional-printed Ti-6Al-4V., *Scientific Reports*, vol.6, 26039. DOI: 10.1038/srep26039.,2016
- Van Arkel, A.C. *History and Extractive Metallurgy*. In *Titanium—Physical Metallurgy, Processing, and Applications*; ASM International: Cleveland, OH, USA, 2015.
- Vilaro, T, Colin, C., and Bartout, J.D. As-Fabricated and Heat-Treated Microstructures of the Ti-6Al-4V Alloy Processed by Selective Laser Melting, *Metallurgical and Materials Transactions A*, vol.42, no.10, pp. 3190- 3199, 2011.
- Yun Bai, Xin Gai, Shujun Li, Lai-Chang Zhang, Yujing Liu, Yulin Hao, Xing Zhang, Rui Yang, and Yongbo Gao, Improved corrosion behavior of electron beam melted Ti-6Al–4V alloy in phosphate buffered saline, *Corrosion Science*, vol.123, pp. 289-296, 2017. ISSN 0010-938X, <https://doi.org/10.1016/j.corsci.2017.05.003>.
- Zhang, L. C., and Attar, H., Selective Laser Melting of Titanium Alloys and Titanium Matrix Composites for Biomedical Applications: A Review, *Advanced Engineering Materials*, vol.18, issue 4, pp.463-475, 2016.
- Zhang, L. C., Klemm, D., Eckert, J., Hao, Y. L., and Sercombe, T. B., Sercombe, Manufacture by selective laser melting and mechanical behavior of a biomedical Ti–24Nb–4Zr–8Sn alloy, *Scripta Materialia*, vol. 65, issue 1, pp. 21-24, 2011.ISSN 1359-6462, <https://doi.org/10.1016/j.scriptamat.2011.03.024>.
- Zhao, H., Microstructure Heterogeneity in Additive Manufactured Ti6Al4V. Ph.D. Thesis, The University of Manchester, Manchester, UK, 2017.

Zhao, S., Li, S. J., Hou, W. T., Hao, Y. L., Yang, R., and Misra, R. D. K., The influence of cell morphology on the compressive fatigue behavior of Ti-6Al-4V meshes fabricated by electron beam melting, *Journal of Mechanical Behavior of Bio-medical materials*. vol. 59, pp. 251-264 .2016.

Biography

Dr. M.B. Kiran is an Associate Professor in the Department of Mechanical Engineering, School of Technology, Pandit Deendayal Petroleum University, Gandhinagar, Gujarat, INDIA. He earned his graduation (B.E.) from the University of Mysore in 1987. He did his post-graduation (M.E.) in Production Engineering from P.S.G. College of Technology (1991) and Doctoral degree (Ph.D.), in Surface Metrology from Indian Institute of Technology (I.I.T.), Madras in 1997. He has Industry/Research/Teaching experience of 25 years. He has published technical papers in many reputed national/international journals and conferences. He is a member of the Project management Institute (P.M.I.), U.S.A. He is a certified project manager (P.M.P.) from P.M.I. He has completed many mission-critical projects. He has conducted many training programs for working executives.