Advancement in the application of alloys and composites in the manufacture of aircraft component: A review

F.M Kgoete¹, A.P.I Popoola¹, O. S. I. Fayomi¹, ²
Department of Mechanical Engineering, Covenant University, P.M.B 1023, Ota, Nigeria
Department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology, P.M.B. X680, Pretoria, South Africa.

*Corresponding author: F.kgoet@gmail.com, ojo.fayomi@covenantuniversity.edu.ng

Abstract
Failures in aerospace structural components have catastrophic consequences, which results in loss of lives and of the aircraft. Failure occurs when a component or structure is no longer able to withstand the stresses imposed on it during operation. Application requirements of aerospace components involves high durability in order to withstand high temperature and pressure environments (such as leaving the earth’s atmosphere or exposure to burning rocket fuel) and must be light weight for easy lifting and fuel efficiency for rockets. Compressor blades in aero-engines are designed for many distinct functions and are required to withstand high temperatures imposed on them by high rotational speed in the form of large centrifugal load and aerodynamic force applied as a function of pressure rise through each stage of the compressor. The paper reviews the advancement in the application of alloys and composites in the manufacture of aircraft component.

Keywords: Failure; Structure; Composite; Environments

1. Introduction
The aerospace industry utilizes titanium made components, including engine fans, compressor blades, air frames, and fan casings [1]. Titanium is the ninth most abundant element in the earth’s crust and the fourth most abundant metallic element [2]. In nature, it is found in the form of rutile (Titanium dioxide, TiO₂) and ilmenite (Titanium iron oxide, FeTiO₃). Titanium is as strong as steel, but its density is only 56% that of steel thus giving it the highest strength-to-weight ratio compared with any of today’s structural metals [3]. Titanium has long been known to have attractive combination of mechanical properties compared to other common structural materials, the high cost associated with the extraction of the metal from the mineral sources and cost of processing the raw titanium metal powder into usable products also hinders its application in many industries [4].

The need to replace iron based metals with lighter and stronger materials to obtain high fuel efficiency; reduction in material and processing costs has led to the use of lightweight materials such as titanium and aluminium in most industries [5]. Ti6Al4V alloy is an extensively used alloy in the titanium industry accounting for 60% of the total titanium production with about 80-90% being used for engineering structural parts [6]. The main interest for its use is derives from its beneficial properties, such as low density, low modulus elasticity, excellent corrosion properties and biocompatibility [7].

2. Alloys as protective device against material degradation
2.1 Ti6Al4V Alloy
In 1954, Ti6Al4V alloy was made known through the addition vanadium and aluminium to titanium. The addition of these two elements was for α and β stabilization. It is the most prevalent alloy and account for more than 50% of Ti alloys used today [8]. This alloy has interesting mechanical resistance owing to its native oxide layer [9]. At temperatures lower than 882°C, Ti6Al4V alloy has α (HCP) phase consisting of a lamella crystal structure and
above this temperatures it converts to β (BCC) martensitic phase [10]. When the alloy solidifies, it starts as the β phase and go through the α single phase state resulting in α+β two phase structure. Manipulating transformation reaction of Ti based alloys results in a phase that consists of two phase structures. This manipulation takes benefit of the mechanical characteristics of Ti based alloys which depends on their microstructure. The α phase of the alloy provide enhanced mechanical characteristics for example improved hardness and resistance to wear while β phase of the alloy offers improved relative strength against corrosive environments.

2.1.1 Titanium alloys employed for aerospace application
The space engineering has been the marketer for the growth and application of advanced engineering materials. The need for these materials is impelled by the performance requirements of a component, which is generally an important part of an intricate procedural system. The high usage of titanium alloys in the aerospace industry lies in the good properties exhibited by the alloys. They possess great corrosion resistance and specific strength to weight ratio which are essential for aerospace industry. To name a few, the alloys hold great corrosion resistance and specific strength to weight ratio which are essential for aerospace industry [11]. In marketable aeroplane engines, titanium alloys are used to make fan blades, compressors, discs and critical rotating components. Other than Ti6Al4V alloy which is the greatest frequently employed materials among titanium alloys, Ti6A2Sn4Zr-2Mo and Ti3Al-2.5V alloys have been developed for decades for high strength aero-engine components [12].

2.2 Ti-6Al-2Sn-4Zr-2Mo alloy
This alloy is known as Ti6-2-4-2 and it has been employed in the aerospace and automotive industry aimed at making elevated temperature jet engines as well as creating high performance automotive valves. This type of alloy is a near alpha titanium alloy recognised for the high strength coupled with excellent corrosion resistance characteristics.

2.3 Ti-3Al-2.5V alloy
This alloy consists of one vital application and has found wide usage in the aerospace and hydraulic tubing industry. The alloy has been useful in making high pressure hydraulic lines, functioning with pressures ranging up to 28 MPa with particle sizes from 6.3 to 38 mm. Ti-3Al-2.5V alloy can be produced into strips, rolled into foil and can be used for honeycomb core manufacturing which requires strength superior than commercially pure titanium (CP-Ti) [13].

3. Protective ability of Composite Materials
Manufacturing of composite materials has been identified to be the simplest and better way to improve and achieve materials that exhibit outstanding properties with much functionality [14]. Composite materials are defined as materials that are composed of two or more key constituents with significant differences in both physical or/and chemical properties, such that once blended; gives a tarn of inimitable distinctive features from those of separate components [15]. The separate components stay separate and divergent within the completed structure. The novel material may perhaps be desired for many reasons: materials with higher strength, lighter and high stiffness, less expensive and high damping capacity when compared to traditional materials. The presence of amalgamated material can be found in two constituents: matrix and reinforcement. Every single ration of this constituent is prerequisite. In actual fact, matrix materials surround and offer backing to the reinforcement materials by safeguarding their virtual places. The reinforcement imparts on their mechanical and physical properties to enrich the matrix properties. Some composite that will be conferred in this section includes MMC (Metal Matrix Composites), CMC (Ceramic Matrix Composite) and MCC (Metal Ceramic Composite).
3.1 Metal matrix composite (MMC)

MMCs are referred to, as materials where firm ceramic additives stay entrenched in ductile metal/alloy matrix and conglomerate metal characteristics (ductile and durability) with ceramic characteristics (high strength and modulus) [15, 16] defined MMC’s as a metal that combines different characteristics of more than one material resulting in physical and mechanical characteristics that are impossible to obtain. They are prepared by distributing a strengthening additive into a metal medium. Utmost reinforcing exterior can be covered to avoid a chemical retort with the matrix. For illustration, carbon fibers are used in aluminium or polymer matrix to produce composites that exhibit low density and high strength. Hence, they provide long time function in automobile; wear processes and thermo-mechanical management [17, 18]. MMCs are almost constantly expensive than the more predictable materials they are substituting. In view of this, the usages are for improved properties and performance which can justify the extra cost. The applications are often in automobile, aerospace, space system electronics and civil structure [19].

3.2 Ceramic matrix composite (CMC)

CMCs are a section of composites materials that contain ceramic fibers interleaved in a ceramic environment. The greatest reason for enhancing and developing CMCs remained overcoming the snags linked with the traditional ceramics such as SiC, Al2O3, AlN, silicon nitride and ZrO2. The main drawback of conventional ceramics is that they effortlessly break with powerful mechanical or thermal-treatment loads originated by insignificant flaws or abrasions. The crack resistance is often very low when considering individual properties. Sometimes, increasing the crack confrontation or breakage durability, units of monocristaline whiskers or platelets are sometimes entrenched into the medium. The major applications are for hard material production and in fabrication of ceramic cutting tools [20, 21], mentioned that ceramic material composites for instance silicon carbide-silicon carbide, carbon-silicon carbide and carbon-carbon are actually well-thought-out as the key aspirants for workings and subsystems in the field of satellite (near-sun) missions, defence, aerospace mission (e.g. body flaps) and for industrial applications under life-threatening environmental settings. A perilous concern for an extensive usage of ceramic material composites is the enlargement of reasonable, dependable and accessible amalgamation techniques to bring together enormous constituents into extra intricate structures.

3.3 Metal ceramics composites (MCC)

Metal ceramics composites are produced from metallic and ceramic proportions, where a metallic particulate material is added with ceramic toughened particulates. This combined exertion results in probable amalgamation of low weight metal with ceramics particles [22]. Frequently, the fabrication of MCC is for light-metal components which are intended specifically for automotive and aerospace engineering. The over-all goal is to reinforce the lightweight particles with advanced ceramics endurable to resist tribological, mechanical or high temperature stresses.

4. Material formation via sintering

Is a route of manufacturing materials from powder, through heating in a furnace lower than its melting point so that bonding occurs by diffusion of atoms. Hence, [22] referred to sintering as diffusion controlled process. The process results in distinct powder particulates adhering to each other to form a solid [23]. This technique serves as the most remarkable principal step in fabrication of several solid-state materials, where powders or pressed compacts of ceramic or metals are bonded together to form a unified solid [24]. Sintering routes happen at lower temperatures and for that reason are highly beneficial for refractory materials fabrication. The ultimate structure and characteristics of the products compare intensely to the percent densification accomplished in the system [25]. The main aim of this stage is regularly to realise just how operational parameters such as temperature, particle size,
applied pressure, particle packaging, composition and sintering atmosphere influences the microstructure of the developed composites. The four categories of sintering formed during heat treatment are explained below.

4.1 Solid-State Sintering
Solid-state sintering, consist of simply solid phases at the sintering temperature. This type of method involves heating the powder to allow solid-state diffusion and bonding of the particles together to occur. The particle bonding is initiated at the contact point, which then grows into necks, reducing the pores between the particles. It is also defined as a state in which densification is reached through variations in particle profile, without particle rearrangement or the existence of liquid. [26], described solid state sintering as a widely used material processing and manufacturing method in which final sintered material microstructure is affected by mechanical and chemical properties (viscosity, diffusivity and chemical potential, etc.) along with external processing factors determined by the sintering condition.

4.2 Liquid-Phase Sintering
This sintering technique consists of fluid and dense particulates where the fluid particles can be existent throughout the whole process or through a particular phase of the sintering cycle. The process employs two elementary ways to achieve a fluid stage: 1) the use of varied powders of divergent properties; and 2) manipulation of interface bonds that forms between two or more components. Liquid phase generally follows after melting or eutectic liquid formation stage. Also, this fluid can be moreover temporary or enduring throughout the whole sintering cycle, liable on the solubility relationships. Low, Robertson and Schaffer, [27] explored the extreme permeability of elemental titanium powder composites after liquid-phase sintering. The authors observed bulge and extreme permeability after mixing Si/Ni with Ti powder by hydride-dihydride route when liquid was present. This was ascribed to the hydrogen which was desorbed into openings, which altered the compression balance amongst the sample and the medium which opposed the sintering pressure, instigating expansion.

4.3 Viscous sintering
Viscous sintering, happens when amorphous solids are formed of glassy particles which allows a flow of materials when a force is applied. Materials with high viscosities have slow flows at room temperature, hence during sintering where elevated temperatures are employed, the viscosity of such glasses are intensely reduced. Surface stress properties of materials differ as a function of surface bend. This effect, results in flow of materials being forced near the particle necks, which results in powder densification forming a ceramic dense. This phenomenon is described as Viscous Sintering [28].

4.4 Sintering techniques
Numerous fabrication methods of producing sintered composites are exceedingly accessible. For example the, pressure-less sintering, gas pressure sintering (GPS), hot pressing (HP), as well as spark plasma sintering (SPS). The resultant sintered composites from the above techniques possess varying mechanical and physical properties and they are also used in countless application or industries.

4.4.1 Pressure-Less Sintering (PS)
Pressure-less sintering is defined as the powder compact sintering without applied pressure. Pressure-less sintering permits intricate shapes to be mass produced frugally and it also requires extended dwell time at target temperatures. Another disadvantage of pressure-less sintering is the fact that with the technique it is hard to attain low porosity percentages in compositions with fewer additives due to absence of pressure [29, 30]. Synthesised and pressure-less sintered titanium aluminium carbide (Ti2AIC). During preparation stage, pure Ti2AIC powder was heated with powder mixture of Ti:Al: TiC at 1300°C for a period of 4 hours. Ti2AIC compacts used for pressure-less contained 5% Al2O3, Y2O3, MgO, CaO or TiO2 which got heated at 1400°C for 2 hours in Ar. The powder blend was uniaxially pressed at 7
MPa into a 20 x 20 x 5 mm rectangular sample. Incorporation of oxide constituents brought about a decrease in the fracture toughness hence fabrication by this technique is not desirable due to the absence of pressure during compaction.

4.4.2 Gas Pressure Sintering (GPS)
This type of technique owns the advantages of hot pressing, pressure-less sintering and hot isostatic pressing [31]. With gas pressure sintering fully densified compacts with no porosity can be obtained with small reinforcement additions. This technique operates at normal sintering temperatures and pressures resulting in further densification and pore eliminations. [32], fabricated solid Si₃N₄ ceramics via GPS (gas pressure sintering) exploring Yb₂O₃ as an improver at a temperature 1900℃ and nitrogen pressure of 1 Mpa. Varying operational parameters such as the influence of Yb₂O₃, packing condition and the effect of time on densification, phase formation, grain boundaries, microstructural evolution and heat conductivity was explored. Observations revealed that gas pressure sintering produced dense Si₃N₄-Yb₂O₃ ceramics exhibiting good mechanical properties.

4.4.3 Hot Pressing (HP)
This is a technique that is used to form powder compacts at a high-pressure, low-strain-rate and high temperatures that bring sintering and creep processes. The powder compacts are attained with concurrent application of heat and pressure. The technique is mostly used for fabrication of hard and brittle materials. [33] studied the properties of hot-pressed titanium and Ti6Al7Nb composite. Commercially pure Ti and Ti-6Al-7Nb alloy powders were hot-pressed at varying operational parameters so to investigate how microstructure and mechanical properties is affected by process parameters. The experiment was conducted by first loading the powders into a die that was made from graphite foil. The powders were pressed at 900 and 1100℃ during 1 hour and 1300℃ during 30 mins at a pressure of 18 MPa. The results showed that producing entirely dense Ti-6Al-7Nb material which is homogeneous, hot pressing must be employed. However, fabrication of composites using this technique is not economical; it waste time due to the higher sintering times.

4.4.4 Hot Isostatic Pressing (HIP)
The technique is employed when there is a need to reduce the amount of pores in metals thus increasing the density. Materials with less pores and high density have good mechanical properties and are workable. The process operates by exposing materials to both elevated temperature and isostatic gas pressure in a vessel containing high pressure. [34] explored hot isostatically pressed Ti6Al4V alloy and the authors were only interested in the mechanical and microstructural characteristics of the alloy. Gas atomization, plasma atomization and hydride/dihydride processes were used to produce pre-alloyed powders. These pre-alloyed powders were then characterized and pressed at 880 and 980 ℃. The authors found the microstructures of the specimen, intensely reliant on beta transus temperature. The authors observed that hot pressed components exhibit alpha-beta mixed phase as compared to the rest of the processes which showed brittle behaviour because of high oxygen content as well as in homogeneities in microstructure.

4.4.5 Microwave Sintering
The technique has been developed over the centuries as a novel mode for consolidation of diverse of materials that have revealed major benefits compared to ancient sintering methods [35]. Microwave sintering combines materials with microwaves which engross the electromagnetic energy and change into heat. The energy sources of this technique are volumetric and generation of heat is through the inside of the sample as compared to other techniques where the heat is generated from an external heat source. It offers uniform, improved densification, fast heating as well as finer microstructures. Operational parameters such as
sample size and shape, microwave energy distribution, and electric and magnetic fields of the electromagnetic radiation are very vital for heating and sintering. [36] explored microwave sintering of titanium. The authors indicated that in order for titanium to be properly sintered, high consolidation temperatures (1200ºC) and high vacuum atmospheres (<10⁻² Pa) are required. This lead the authors to microwave sinter titanium at a temperature of 1200ºC, ranging pressure of 200-800 MPa and vacuum atmosphere of 2.6x10⁻³ Pa. An actual microwave heating rate of 34ºC/Min was attained from 350ºC to 1200ºC. Composites fabricated by this technique are not preferred due to the fact that it involves long sintering cycles (10-12 hr).

4.4.6 Spark Plasma Sintering
Is a blend and fabricating method which allows powders to be consolidated at temperatures below their melting points. The process is time efficient since the intervals between powders particles can be charged with electrical energy [36, 37] referred to the process as a cost-effective, time and energy saving technology for producing Ti6Al4V bulk materials with improved properties. It is employed to manufacture several materials counting metals, composites as well as ceramics. These materials are developed through heating in a furnace so that adherence occurs as a result of diffusion forming a dense compact. The heating is rapid; hence it is said to be a fast sintering method, which uses a self-heating action. However, the technique as compared to many conventional methods offers many advantages such as simplicity of operation and consistency. [38] referred to SPS as an innovative technique that allows shorter sintering times of metals, alloys and metal/alloy.

4.5 Spark plasma sintering mechanism
SPS in many aspects works like hot pressing technique. In both the techniques, the starting materials are poured inside a die made of graphite, and pressure is applied throughout the development. The difference between them lies in the fact that with SPS, the heating source is not external but internal. The internal heating is driven by current which passes through the die and in some other setups through the specimen as well. This suggests that the die serves as a source of heating which allows the specimen to be thoroughly heated inside the die. There have been many disputes in whether SPS utilises plasma or not and this led to many researchers investigating the existence of plasma in spark plasma sintering technique. In previous work done by many researchers, results revealed that no plasma exist in SPS. To expand upon previous results, [39] discussed non-existence of plasma in the method. The authors used in situ atomic emission spectroscopy equipment entailing an elevated temperature fiber optic flame probe and a fiber optic vacuum feed-through. To avert probe damage during sintering, the component was sleeved in a borosilicate glass capillary tube. After vivid study, the authors established that SPS method does not use plasma, either through early or last step of the process [40].

Widespread exertions have been made in considering SPS as an emerging and capable system for fast densification of innovative materials with numerous applications. This is attributed to operational parameters, difficulty in thermal, electrical and mechanical processes that are involved in sintering. Particularly, the presence of spark plasma and existence of discharge in the sintering process are exceedingly debatable hence, [41] attempted to proof the presence of spark discharge in SPS opposing the work done by [42].

4.6 Effects of operational parameters on sintering
The quality of sintered composites produced by this technique depends on several operational parameters. They have a key effect on the interface, combination and phase transformation that eventually affect their overall properties. The parameters include temperature, time,
atmosphere, heating rate, sintering pressure, and alloy composition. It is for this reason that processing parameters need to be carefully chosen and controlled during consolidation process to fabricate fully dense alloys possessing the required enhanced mechanical properties [43]. Any change in the sintering parameters influences the whole material domain [44]. Holding time and heating rate have negligible influence on resultant density, however, it has been proven through Design of Experiment (DoE) approach that sintering pressure and temperature are relative to density, hence it is for this reason that greater control of these variables is required for optimum sintered properties. Generally, these parameters or variables are interdependent and are discussed below.

4.6.1 Temperature
In the spark plasma sintering method, the leading and effective operational parameter remains temperature. This parameter controls the features that depends on microstructure [32], indicated that to control sintering temperature, time, ramp rate, pulse period, and current must be considered. Microstructural features are highly influenced by temperature and are in control of mechanical characteristics of metals. Therefore, temperature is significant in enhancing ductility and strength of materials. [29] investigated the importance of temperature on density, toughness and wear behaviour of SPS Ti6Al4V composites. The sintering process was done at a temperature ranging from 650 to 850°C while holding rate was held constant. The results obtained showed that the density and hardness were enhanced significantly as the sintering temperature increased this was attributed to pore size reduction and higher densities as the temperature increased [44]. made an attempt to investigate the influence of SPS temperature on the properties displayed by Fe-30%Ni composite. The results of the work done by the author indicated that the RD, hardness and crack morphology relied on temperature which ultimately affected microstructure. Furthermore, density of compacts increased with increasing temperature which facilitated necking.

4.6.2 Holding Time
Holding time is defined as the highest temperature at which desired properties are achieved. The parameter depends on the temperature during process, and the vital porosity and the pore form. If sintering occurs at high temperatures holding time is shorter while at low temperatures it is higher. Adegbenjo et al. (2017:35), varied the parameter (holding time) between 2 and 10 min during the study of low temperature spark plasma sintered irregular shaped Ti6Al4V powders with enhanced properties. The authors work was aimed at lowering excessive cost associated with the processing of the alloy powders into bulk materials. The sintering of as-received powders was performed in a vacuum at 850°C, 100°C/min heating rate and 50 Mpa pressure. Archimedes’ principle and Vickers indentation method were used for the density and hardness measurements respectively. SEM, EDX and XRD analysis were employed by the authors to characterize the as-received, for microstructural evolution studies, fractography and phase identification of the sintered alloys. The results obtained shows that optimum properties were attained at 6 min holding time with 99.7% relative density and 366 HV of Vickers micro-indentation hardness which led to the author further referring to the SPS method as an affirmed economical and viable route for producing Ti6Al4V alloys with enhanced properties.

4.6.3 Heating Rate
Heating rate is a thermodynamics word which in various engineering sectors designates the quantity of heat a flowing fluid of a definite mass flow rate can engross or release per unit temperature change per unit time. It is important to keep heat up rate as slow as possible, reason being that if the heating is fast the additives may boil and evaporate which eventually will cause the sample to swell and crack. A high heating rate brings about a green compact to the SPS temperature sooner. This phenomenon is restricted by the size of the samples as well as the thermal features of the furnace. Chaim, Shlayer and Estournes (2009:94), evaluated the
consequence of heating rate on grain growth densification using SPS temperature and pressure. After experimental analysis, the author indicated that, higher heating rates and temperatures results in larger final grain sizes and higher relative densities.

5. Conclusions
It is with no doubt that alloys and composite contribute significantly to societal benefit. Currently, it is for this reason that it is very difficult to imagine the aerospace industry without alloys and composite. These alloys bring are presently the backbone for many applications. However, poor tribological, corrosion, mechanical and thermal properties of alloys remains a major challenge in aerospace industry. Hence, there continue to be many demands for improved mechanical and high temperature materials made of alloys to enable further advances and service life of components. Composite materials are now used for bettered and advance increasing developments in the industry.

Acknowledgement
The author appreciates the department of Chemical, Metallurgical and Materials Engineering, Tshwane University of Technology for the support offered to carry out this research work.

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