Recent Developments of Materials used in Air breathing and Advanced Air breathing Engines

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Abstract. Jet engines require special materials that can withstand the demanding environments imposed on the various components and sections, so selection of materials is primary requirement during design of jet engine components. This paper is the study of various materials and their applicability for different components of jet engine for the purpose of enhancing the performance, reliability and durability. Review of materials for different types of jet engines such as turbojet engine, turboprop engine, turbofan engine, turboshaft engine, ramjet and scramjet engine is presented. This paper overviews the properties and materials used for different types of jet engines and can be used for further researchers in the field of jet engine materials.

1. INTRODUCTION

Jet engines are widely used in many applications like aviation and many other energy production vehicles and it is shown in the figure 1. The most widely used air breathing jet engines are the turbojet engine, turboprop engine, turbofan engine, turboshaft engine, ramjet and scramjet engine. In all above engine, working principle is quite same. In engine, there are different series of components existing namely inlet intake, compressor, combustion chamber, turbine and nozzle. The main function of intake is to suck the air, similarly compressor function is to compress the intake air, combustion chamber function is to mix compressed air with fuel, then ignite to produce hot, expanding gases by burning continuously, turbine function is to drive the compressor so that it produces thrust for propelling the aircraft, the main function of outlet is to exit the ignited air and fuel mixture at high velocity.

![Figure 1. Basic configuration of a jet engine [2]](image-url)
1. Properties to be possessed by gas turbine engine materials:
Low cost and light weight are two important properties. Some other properties also required in engines are strength over density, specific strength, corrosion and heat resistivity, resistance to embrittlement at low temperature, low-thermal expansion etc. For improving the fuel efficiency of an airplane lightweight material can be used. This paper mainly focuses about materials used in jet engine structures. Here are some materials used with their properties and application in engine.

1.2 General Materials used in engine section are discussed below
Titanium has high specific strength, light weight, resistance to heat and corrosion, resistance to embrittlement at low temperature. It is mainly used for the fan and the compressor where the temperature is relatively low (600°C or lower) and for turbine blade applications titanium aluminides (TiAl) are being used which is shown in figure 2 because of its light weight blade design, less stress on the rotating part.

![Figure 2. Titanium aluminide turbine blade [28]](image)

Carbon Fiber Reinforced Plastic (CFRP) benefits over other materials at temperature below 200°C. Aluminium alloys costs less and has good castability but less strength and the stiffness against titanium and CFRP, one of the example is aluminum ring for fan case which is shown in figure 3.Superalloys have an extraordinary properties at high temperatures, have excellent mechanical properties and with excellent corrosion resistance. These can be used for combustion chamber, casings after burners etc.

![Figure 3. Large size wrought aluminum ring for the aft fan case of GEnx 1b engine [18]](image)

Composite materials can provide a much better strength-to-weight ratio than metal by 20%, which results in weight reduction, and such comparison is shown in figure 4. The various types in composite materials includes PMC (Polymer Matrix Composite) material which has high tensile strength, stiffness and fracture toughness and has benefit over all other materials, Ceramic Matrix Composites (CMCs) possess properties such as light weight, high strength, toughness and high temperature resistivity up to 1200°C, so can be used in the hot section of the aero engines such as turbine disks. Metal Matrix Composites (MMCs) has less toughness, more expensive and applications include helicopter rotor blades and turbine fan blades, Carbon Matrix Composites have high thermal stability and can withstand up to 300°C but require high manufacturing cost, Fibre-reinforced polymer (FRP) have properties such as high strength, less weight,
Many more materials are used for other applications as Gas Turbine Engine is not a small component as it compromises several sub parts. The following figure 5 shows the temperature profile versus specific strength of materials used in gas turbine.

**Figure 5.** Representation of material requirement between strength and temperature for aero engines [11]

### 1.3 Compositions of materials used in each engine section are discussed below

**Fan Section:** The Fan section is responsible for taking air into the engine so fan should be made of materials which have properties such as light, high stiffness and high specific strength. In order to obtain high propulsion efficiency, the fan has to be bigger in size to have high bypass ratio so material selection is important. In general, for the fan blade titanium, aluminium and stainless steel have been used, where titanium is used often because of its versatile properties. Some of the fan blades are composed with CFRP blades and titanium(Ti-6Al-4V) leading edge for improving the impact resistance towards bird strikes.

**Compressor Section:** In the compressor, the air is compressed which is taken by the fan into the engine. Due to compression of air, the temperature begins to rise therefore, materials required to have high-
temperature strength such as (Ferrous) Fe-, (Nickel) Ni-, and (Titanium) Ti-based alloys. Titanium has been a dominant material in compressor stages of aeroengines. Ti-6Al-4V is used for fan disc and low-pressure compressor discs and blades whose maximum temperature is of about 315°C. Alloy 834 is used in the last two stages of the medium-pressure compressor, and the first four stages of the high-pressure compressor for compressor disc. The maximum temperature limitation for titanium alloys is at the hottest parts, i.e. the discs and blades of the last compressor stages, and the temperature reaches 500°C so Nickel based superalloys which is nearly twice the weight must be used.

Combustor Section: Ignition of air-fuel mixture takes place and the temperature reaches very high, so heat-resistant alloys such as Cobalt and Nickel based superalloys need to be used. Hastelloy–Nickel based superalloy and HA188-Cobalt based superalloys are examples.

Turbine Section: The Turbine function is to generate power to rotate other parts, so it reaches high temperature and pressure. Therefore, the materials required should be having high creep strength, high temperature fatigue strength and high temperature corrosion resistance. The titanium cannot be used for this section as it reaches 1500°C so the materials generally used are Cobalt and Nickel based superalloys because of their high creep strength. Cooling passages design is needed for thermal barrier coating made up of zirconium and Ni-Co-Cr-Al-Y alloys for high temperature corrosion resistance to improve turbine blade performance.

Shaft: Shaft is driven by the turbine and goes through the entire engine which has both low and high temperature environment and it transmits power from the turbine to other engine sections. So, material properties are required are heat resistance, high temperature strength, high fatigue strength, and toughness in order to withstand the high-speed rotation. Therefore, materials used can be Cr-Mo-V(Ferric) steels, Inco-718 and maraging steels. Material requirement and temperature for aero engines is shown in figure 6.

2. LITERATURE SURVEY

2.1 Recent Developments of Turbojet Engine Materials
IkpeAniekan Essienubong et al [2, 5] reviewed material selection process which can withstand the
temperature, creep and cyclic stresses acting on the blade component of high-pressure turbine blade and high-pressure compressor blade of a turbojet engine. So, Nickel based superalloys was chosen as per requirements. C.Rajaravi et al [7] designed combustion chamber by using steel with carbon-carbon composite which resulted in less heat flux, so it reduces the temperature of wall.

KyoSoo Song et al [3] investigated crack initiation caused by the fracture on a turbine blade of a turbojet engine due to the stress concentration and then fractured by the overload at the last moment was found by microstructure and EDX analysis of the blade.

Ernesto Benini et al [4] developed a 200 N static-thrust engine used for both didactic and research activities. This paper describes in detail all the phases required to set-up such an engine. Malcolm Thomas et al [13] explained that the new engine manufacturing, development and certification by number of reasons such as safety, reliability and cost. So, the author discussed the risks and necessary actions required for material insertion with examples.

Prashant Singh et al [6], Goran Sjoberg [18] and Nageswara Rao Muktinutalapati [60] described the availability of materials for the gas turbine engine and temperature limitations, properties of materials used with their compositions and application. The materials discussed were Titanium, Composite material with their types, super alloys etc. Research and development to improve the thermal fatigue can be done by development of techniques for production of uniform and high-density coatings.

Takehiro Okura [14] discussed the latest developed materials for General Electric aircraft engines. The GEnx engines used Titanium and composite for weight reduction and fuel efficiency improvement. Daniel G. Backman [8] and Carlos A Estrada M et al [9] presented a review of advances in structural materials for aircraft engine such as superalloys, composite and inter-metallic materials and with improved manufacturing and new technologies to increase production efficiency, enhance product quality and decrease engine development time.

Mikael Perrut et al [10] presented microstructural, chemical features, mechanical behaviour, coating interaction and environmental effects of two high temperature materials for high and low-pressure turbine blades respectively. Jaishri Patel et al [15] focused on different design blades of gas turbine and the designed the blade based on an industrial gas turbine from reference. The special steels, titanium alloys and super alloys materials were selected which can withstand high elevated temperature, strength to weight ratio.

Srinivas G et al [11] presented the applications, cost-effective and technical capabilities of different turbomachinery components manufacturing techniques, shaping process and coating in aeromechanical applications. Keshav Sharma et al [12] analysed material failure and aimed for reducing the losses by NDT techniques and analysed combustion instabilities caused by pressure oscillations.

### 2.2 Recent Developments of Turboprop Engine Materials

Changduk Kong et al [20, 21] and Hyunbum Park [24] designed propeller blade which was made up carbon/epoxy fabric skin-spar and urethane foam core sandwich. The aerodynamic and stress analysis was carried using finite element analysis (FEA), the bird strike analysis was also conducted using ANSYS. Results found that the designed blade has a good structural integrity and agreed well with the analytical results including deflections, strains and natural frequencies. Results concluded that the proposed propeller has better aerodynamic performance compared to similar existing propellers. Madhusudhan BM et al [22] designed composite propeller which is a combination of CFRP and epoxy resin materials to analyse its strength and deformation using ANSYS software. The stress analysis was conducted to both composite blade and wooden blade. From the results, for the composite propeller the static analysis is in allowable
limit and the deflection is less compared to wooden blade.

Massimo Viscardi et al [19] and A. Grewal [23] focused on self-healing laminates and segmented piezoelectric actuators in primary structural parts of an aircraft such as on outer skin of a turboprop fuselage to achieve a considerable reduction of the internal noise and vibration generated by the propeller source which reduces passenger cabin noise.

2.3 Recent Developments of Turbofan Engine Materials

Srijith Bangaru Thirumalai Raj [27] focused on detailed study of materials used in the front fan blade of turbofan engine by considering operating conditions. The CES software gives a summary of characteristic properties, micro structural changes and manufacturing technique of conventional and advanced materials. Zhenzhen Liu et al [31] carried out series of studies on fan blades of CFM56 engine under centrifugal load and studied the influence of torque under different speeds using CATIA’s (FEA) software to improve the flow capacity by reducing the hub ratio, blade tip cutting speed and average level load.

Takekawa Mitsuhiro et al [28] and Ikuhiro Inagaki et al [32] discussed use of titanium for aircraft parts such as for the fan and the compressor in the fore half section, as it makes engines lighter thus lighter aircraft. Joshua From [35] studied the composite material and their use in turbo fan engine such as for fan blades, fan case due to their enormous number of advantages. Polyminia Dileep et al [33] designed and analysed the fan blade with different materials such as composite fan blade with honeycomb sandwich construction, PMC and honeycomb aluminium core. Results were compared with basic fan blade made of titanium which concluded that composite fan blade has less deformation because of high stiffness.

Marco Anghileri et al [30] discussed the impact of bird strike onto a nacelle made up of composite material of turbofan engine. So, analysis was performed using LSTVC LS-Dyna 970 software to avoid failure of material caused by bird strike. Vimal Raj K et al [29] and Katherine M. Handschuh et al [34] designed, fabricated and tested fatigue analysis, impact resistance for a simplified composite blade subcomponent to resist a bird strike event and to calculate margin and life of the fan blade which reported improvement in impact resistance and fatigue life.

C. Sandu [25] proposed bionic technology which resembles bird bone structure to manufacture light fan blades, vanes and housings due to its smaller density and high strength compared to composites materials, so this technology can lead to very light turbofans. Rula M. Coroneos [26] designed a sandwich composite turbofan engine blade with optimum number of plies from a solid metallic baseline model. The structural analysis and optimization resulted in lighter blade design and mass savings compared to metallic blade.

2.4 Recent Developments of Turboshaft Engine Materials

V. Infante et al [36] presented detailed analysis of the failure for a compressor rotor blades of stage 1 from helicopter engine due to contact with inlet vanes blades, material analysis was performed to determine the cause, which revealed that large plastic deformation occurred with the collision of different components. M. Giglio [41] conducted fail safe behaviour of a composite rotor hub to find out the failure cause which started due to high stressed area and it propagated to whole section. Nicholas Bojdo et al [39] explained a novel approach to the effects of desert particulate composition on helicopter engine as it clogs the cooling holes, so a choking effect leading to a reduction in the surge margin was created which results in reduction in life.

M R Edwards [38], Michael J. Vick et al [40] and Bosko Rasuo [37] reviewed materials such as composite and ceramic materials essential with their use for modern military helicopter and also presented the design, fabrication, structural and fatigue analysis, static and dynamic testing for tail rotor blade of helicopter which is made of composite laminated materials as it can provide high degree of damage tolerance with
exceptional high structural damping.

2.5 Recent Developments of Ramjet Engine Materials

J.V. Sai Prasanna Kumar [43] performed manufacturing of ramjet engine and tested full assembly, performed analysis of temperature with different fuels where temperature, velocity and pressure distribution was found. Clinton Humphrey [45] described the design and fabrication of inlet of a ramjet engine with low carbon mild steel material to accommodate the high pressure of the inlet.

Ken Goto et al [42] studied CFRP, carbon-carbon composites for application to a turbine disk of Air turbo ramjet engine where fracture analysis was carried out to find out the fly-out behavior. Abhishek Sharma et al [44] and Riheng Zheng et al [46] developed ramjet nozzle with Carbon fibre reinforced Silicon Carbide (C/SiC) composite along with a lining of ceramic material to reduce the erosion as the gases coming out of nozzle have high pressure, temperature, velocity, are rich in oxygen, so engine gets eroded which leads to structural failure.

Steffen Beyer et al [47] studied advanced fuel cooled structures for application of heat exchanger in a dual-mode ramjet with integrated fuel injection strut design by using PTAH technology by using fuel cooled ceramic structures.

2.6 Recent Developments of Scramjet Engine Materials

Terence M.F. Ronald [50] described the structural materials development program, followed approaches, and general properties being developed, materials studied for National Aero-Space Plane. Alvaro Francisco Santos Pivetta [51] presented the structural numerical analysis using FEM for a VHA 14-X S which is technological demonstrator of a hypersonic air breathing system. Structural materials for the stringers, ribs and coating materials for the thermal protection systems were specified. Felipe Jean da Costa et al [53] conducted analysis for the Brazilian 14-X Hypersonic Aerospace Vehicle, using long stainless steel waverider model technology for providing lift and scramjet technology for providing supersonic combustion where both have been experimentally investigated.

J. Steelant [56] and M. Bouchez et al [57] investigated on Aerodynamic and Thermal Load Interactions with Light weight Advanced Materials for High Speed Flight project with different materials (CMC, metallic) and different cooling techniques to withstand ultra-high temperatures and heat fluxes to enable high flight speed Mach 3. F.Zander [52] conducted analysis for proposed scramjet combustor with heat transfer to walls and fuel showed that the combustor never reaches excess temperatures using composite materials and regenerative cooling.

S.L. Draper et al [55] determined to reduce weight of hypersonic propulsion system structures by utilizing TiAl for a stiffener structure in an inlet, combustor, and nozzle section and inlet cowl flap of a hypersonic scramjet engine. Darrel R. Tenney et al [59] discussed the materials and structures such as airframe, control surfaces, nose cap where carbon-carbon metal was used with heat-pipe leading edge concept for hypersonic vehicles. This paper addressed challenges of materials and structures for high temperature applications.

Tumde Nishit et al [48], Gautam Choubey et al [49] and Tjong et al [54] explained a review of composite materials with its advantages, properties, types and various applications includes PMC in scramjet combustor due to quality to weight ratio and safe properties. CMCs were used in motor hot segment segments and MMC is used for high temperature restoring quality and sturdiness.

2.7 Recent Developments of Composite Engine Materials

Patrick Spriet et al [1] and Mohammad Arif et al [16] studied the brief review of the current status of
composites material due to its advantages with their types and use in jet engine and discussed progressive development for further uses in future. L. Jinsheng Ma [58] analysed the application of CFRP, MMC, CMC and resin matrix composites in parts of auto-mobile engines, civil aircraft engines, military aerospace engines, solid rocket motors, transcendental ramjet and scramjet applications. Baroumes et al [17] used CMCs for self-sealing technology for matrix and multilayer woven reinforcement.

2.8 Summary of Literature Survey

2.8.1 Turbojet Materials Summary
Applications of ceramic composites and its coatings are used to turbojet engines to withstand temperature. Nickel based super alloys was chosen as right material for high pressure turbine blade and compressor blade as it can withstand the high temperature, creep and cyclic stresses. The use of steel with carbon-carbon composite for combustion chamber increases efficiency. Super alloys, composite and intermetallic materials with improved manufacturing methods enhance product quality and decreases time.

2.8.2 Turboprop Materials Summary
Self-healing laminates and piezoelectric actuators placed in skin of a turboprop fuselage can reduce internal noise and structural vibrations generated by the propeller. The use of carbon/epoxy fabric skin-spar which has properties such as lightness, high strength and stiffness for propeller blade gives good structural integrity. Composite propeller with a combination of CFRP and epoxy resin materials has allowable stress limit and less deflection compared to wooden blade.

2.8.3 Turbofan Materials Summary
Bionic technology was used for turbofans to produce low density materials. Using optimum number of plies in a sandwich composite turbofan blade resulted in lighter blade design. Titanium aluminide blade can cost less due to its less density and replacing the metallic fan blade with composite material improves the fatigue life so can be used for the fan and the compressor. For the turbine and the combustion chamber, a nickel or iron based alloy is used in turbofan engine. Fan blade with different composite materials were compared with basic titanium fan blade concluded that composite fan blade has less deformation.

2.8.4 Turboshaft Materials Summary
Materials such as aluminium alloys and fibre-reinforced composites with properties high specific strength and stiffness are considered for the modern military helicopter. The effect of desert particulate composition leads to clog cooling holes which reduces life of helicopter engine.

2.8.5 Ramjet Materials Summary
CFRP and carbon composites were used turbine disk of ATREX increases toughness of the fiber. Ramjet engine gets eroded easily which leads to structural failure and this can be reduced by using composite materials. Composite materials with lining of ceramic material will ensure minimum erosion for the ramjet nozzle. For inlet material used is of low carbon mild steel to accommodate high pressure.

2.8.6 Scramjet Materials Summary
The materials should have properties such as lightweight, high tolerance for cyclical loads and can form complex shapes. Materials such as metal alloys, CMC, MMC and carbon composites were used in various hypersonic vehicles. PMC were used in scramjet combustor due to less weight and safe properties. TiAl titanium alloy is used for parts such as inlet, combustor, and nozzle section of engine as it reduces weight.

2.9 Research Gap
The titanium is used for many parts in aircraft engine but cannot sustain the temperature near combustion chamber and turbine. So, a new alloy of titanium should be developed which can reach 1200ºC. The super alloys have the mechanical properties but scope of developing new materials is less due to high
maintenance knowledge.

3. CONCLUSION

Turbojet engine is basic type of jet engine and it used for small aircrafts which require low thrust. For the parts such as turbine and compressor blades, nickel-based superalloy must be chosen whereas for combustion chamber, steel with carbon-carbon composite or superalloys can be used. The turboprop engine has propeller at front attached to turbine shaft and it is used for aircraft such as fighter aircraft which require high initial thrust, travel higher altitudes. The propeller has to be made up of composite material for better aerodynamic efficiency. The turbofan engine has fan at front attached to turbine shaft and it is used for carrying passengers, cargo. The fan has to be made up of titanium alloy or composite material to improve fatigue life. The turboshaft engine is used for high maneuvering of helicopters and ceramic materials can be used for turbine rotors.

Ramjet engines operate with supersonic speeds and are used for missiles so temperature resistance materials such as composites are used whereas scramjet engines operate at hypersonic speeds above Mach 5 and are used in weapons and missiles so temperature resistance materials such as PMCs for combustor, CMCs for motor hot segments, TiAl for inlet, nozzle, combustor and refractory materials are used.

REFERENCES

[1]. Patrick Spriet and Georges Habarou 1997 Applications of Ceramic Matrix Composites to Turbojet Engines: Overview of the SEP experience vol 127 (Switzerland:Key Engg. Mater.) pp 1267-1276
[2]. IkpeAniekan Essienubong, Owunna Ikechukwu, Patrick. O. Ebunilo and Ememobong Ikpe 2016 Material Selection for High Pressure (HP) Turbine Blade of Conventional Turbojet Engines vol 1 no 1 (American J. of Mech. and Industrial Engg.) pp 1-9
[3]. Kyo-Soo Song, Seon-Gab Kim, Daehan Jung and Young-Ha Hwang 2007 Analysis of the fracture of a turbine blade on a turbojet engine vol 14 (Elsevier) pp 877-883
[4]. Ernesto Benini and Stefano Giacometti 2007 Design, manufacturing and operation of a small turbojet-engine for research purposes vol 84 (Elsevier) pp 1102-1116
[5]. IkпеAniekан, E OwunnaIkechukwu, Ebunilo P.O and EmemobongIkpe 2016 Material Selection for High Pressure (HP) Compressor Blade of an Aircraft Engine vol 2 no 4 (Int. J. of Advanced Mater. Res.) pp 59-65
[6]. Prashant Singh, Kalpit P. Kaurase and Gaurav Soni 2015 Study of Materials used in Gas Turbine engine and swirler in combustion chamber vol 1 no 1 (IJARIIE) pp 39-46
[7]. C.Rajaravi, P.Yogesh and B.Rajalingam 2018 Heat Transfer Analysis of Carbon-Carbon Composite Materials in Gas Turbine Combustion Chamber (Int. J. of Pure and Applied Mathematics) vol. 118 no. 5 pp 805-814
[8]. Daniel G. Backman and James C. Williams 1992 Advanced Materials for Aircraft Engine Applications (Science) vol 255pp 1082-1087
[9]. Carlos A Estrada M 2007 New Technology Used in Gas Turbine Blade Materials no. 36 (Universidad Tecnologica de Pereira:Scientia et TechnicaAno XIII) pp 297-301
[10]. Mikael Perrut, Pierre Caron, Marc Thomas and Alain Couret 2018 High temperature materials for aerospace applications: Ni-based superalloys and gamma-TiAl alloys vol 19 no. 8 (Elsevier Masson) pp 657-671
[11]. Srinivas G, Raghunandana K and Satish Shenoy B 2018 Recent developments in turbo machinery component materials and manufacturing challenges for aero engine applications (IOP Conf. Ser.: Mater. Sci. Engg. 314) 012012
[12]. Keshav Sharma, Armaan Aditya and G. Srinivas. 2019 Material failure analysis and engine combustion instabilities of both air and non-air breathing engines (Mater. Today Proc. Elsevier)
[13]. Malcolm Thomas and Susan Murray and David Furrer 2010 Introducing New Materials into Aero Engines - Risks and Rewards, A User's Perspective ed E.A. Ottet al (7th Int. Symp. on Super alloy and derivatives) pp 3-11
[14]. Takehiro Okura 2015 Materials for Aircraft Engines
[15]. Jaishri Patel, Jaishri Dubey, Rajni Dewangan and Shailendra Kumar Bohidar 2014 Review of Process and Material used for Design of Gas Turbine Blades vol 3 no 8 (Int. J. of Sci. Res. Eng. and Technol.) pp 1126-1130
[16]. Mohammad Arif, Mohammad Asif and Israr Ahmed 2017 Advanced Composite Material for Aerospace Application-a Review vol 7 no 2 (Int. J. of Engg. and Manufacturing Science) pp 393-409
[17]. L. Baroumes, E. Bouillon and F. Christin 2004 An Improved Long Life Duration Ceramic Matrix Composite Material for Jet Aircraft Engine Applications (24th Int. Congress of The Aeronautical Sciences) pp 1-10
[18]. Goran Sjoberg 2008 Aircraft Engine Structure Materials vol 13 (Volvo AeroCorporation) pp 1-24
[19]. Massimo Viscardi, Maurizio Arena, Giuseppina Barra and Liberata Guadag (Int. J. of Mech. Engg.)
[20]. Changduk Kong, Hyunbum Park, Kyungsun Lee and Won Choi 2012 A Study on Structural Design and Analysis of Composite Propeller Blade of Turboprop for High Efficiency and Light Weight (Italy: 15TH European Conf. on Composite Materials) pp 1-12
[21]. Changduk Kong and Kyungsun Lee 2013 Study on Design of High Efficiency and Light Weight Composite Propeller Blade for a Regional Turboprop Aircraft vol 30 no 1 (Int. J. Turbo Jet Engines) pp 33-42
[22]. Madhusudhan BM and P.V Srichari 2014 Design and Analysis of Composite Propeller Blade for Aircraft vol 4 no 9 (Int. J. of Engg. Res. and Applications) pp 79-82
[23]. Grewal, A, Zimcik. D. G, Hurtubise. L and Leigh.B 2000 Active Cabin Noise and Vibration Control for Turboprop Aircraft Using Multiple Piezo-electric Actuators vol 11 (J. of Intelligent Mater. Sys. and Struct.) pp 438-447
[24]. Hyunbum Park 2014 A Study on Impact Damage Analysis of Composite Propeller Blade of Turboprop Aircraft vol 577-578 (Switzerland: Trans Tech Publications) pp 489-492
[25]. C. Sandu, S. Vintila, M. Sima, F. Zavodnic, T. Tipa and C. Olariu 2018 Manufacturing Aerospace Components using Bionic Technology vol 12 (Int. J. of Systems Applications, Engg. and Development) pp 168-175
[26]. Rula M. Coroneos 2012 Structural Analysis and Optimization of a Composite Fan Blade for Future Aircraft Engine vol 217632 (Ohio: NASA) pp 1-50
[27]. Srijith Bangaru Thirumalai Raj 2017 Advanced Material for Front Fan Blade Manufacturing vol 3 no 5 (Imperial J. of Interdisciplinary Res.) pp 80-88
[28]. Takekawa Mitsuhiro And Kurashige Masashi 2014 Making Lighter Aircraft Engines with Titanium Aluminide Blades vol 47 no. 1 (IHI Engineering Review)
[29]. Vimal Raj K and Dhanjan Gan G 2018 Improving fatigue life of gas turbine fan blade using advanced composite materials (IOP Conf. Series: Materials Science and Engineering 455) 012035
[30]. Marco Anghileri, Luigi M Castelletti, FaibolInvernizzi and Marco Mascheronibird strike onto the composite intake of a Turbofan engine (European LS-Dyna Users Conf.)
[31]. Zhenzhen Liu, Zhixiong Chen and Jin Chen 2018 The Strength Analysis of CFM56 Engine Blade (ICMAA)
[32]. Ikuhiko Inagaki, Tsutomu Takechi, Yoshihisa Shirai And Nozomu Ariyasu 2014 Application and Features of Titanium for the Aerospace Industry vol 106 (Nippon Steel and Sumitomo Metal Technical Report) pp 22-27
[33]. Polyminna Dileep, G Rajkumar C. Mohan Naidu 2019 Strength Assessment of Fan Blade with Different Materials vol 6 no 1 (Int. J. of Sci. Res. in Sci. and VTechn.) pp 266-283

[34]. Katherine M. Handschu, Sandi G. Miller, Matthew J. Sinnott, Lee W. Kohlman, Gary D. Roberts, J. Michael Pereira and Charles R. Ruggeri 2014 Materials, Manufacturing and Test Development of a Composite Fan Blade Leading Edge Subcomponent for Improved Impact Resistance (Cleveland:NASA)

[35]. Joshua Fromm Composite Fan Blades and Enclosures for Modern Commercial Turbo Fan Engines pp 1-12

[36]. V. Infante and M. Freitas 2019 Failure analysis of compressor blades of a helicopter engine vol 104 (Elsevier) pp 67-74

[37]. Bosko Rasuo 2011 Helicopter Tail Rotor Blade from Composite Materials: An Experience (SAE International)

[38]. Edwards. M. R 2015 Materials for military helicopters vol 216 (Proc.Instn. Mech.Engrs.) pp 77-88

[39]. Nicholas Bojdo and Antonio Filippone 2014 Effect of Desert Particulate Composition on Helicopter Engine Degradation Rate (40th European Rotorcraft Forum)

[40]. Michael J. Vick, Andrew Heyes and Keith Pullen 2010 Design Overview of a Three-Kilowatt Recuperated Ceramic Turboshaft Engine (Proceedings of ASME TurboExpo) pp 1-14

[41]. M. Giglio, A. Manes and F. Vigano 2009 Experimental and Numerical Investigation on Fatigue Failure of Composite Helicopter Main Rotor Hub (Ottawa:ICF12) pp 1-10

[42]. Ken Goto, Hiroshi Hatta, Yasuo Kogo, Hiroshi Fukuda, Tetsuya Sato and Nobuhiro Tanatsugu 2003 Carbon-carbon composite turbine disk for the air turbo ramjet engine (ATREX) vol 12 no 2-3 (Adv. Composite Mater.) pp 205-222

[43]. J.V. Sai Prasanna Kumar, Revathi. K, Sabarigirinathan. R, Santhosh Kumar. M, Udhaya Kumar. T and Viswanath. S 2016 Design Fabrication and Performance Analysis of Subsonic Ramjet Engine vol 03 no 04 (Int. Res. J. of Engg. and Tech.)

[44]. Abhishek Sharma and Ankur Mahajan 2017 Prevention of Erosion by Introduction of Ceramic Matrix Material for Ramjet Nozzle vol 4 no 3 (Int. J. of Aerospace and Mech. Engg.)

[45]. Clinton Humphrey 2013 Design and Fabrication of a Ramjet Inlet (California Polytechnic State University)

[46]. Riheng Zheng, Zhiyong Li, Jingmin Chen, Lihan Lianmei Li, Litong Zhang, Laifei Cheng, Xiaoying Liu, Chao Chen and Hui Mei 2014 Development of Full Scale Ramjet Nozzle with C/Sic Ceramic Matrix Composite ed Litong Zhang and Dongliang Jiang (John Wiley and Sons, Inc) pp 681-694

[47]. Steffen Beyer, Stephan Schmidt-Wimmer, K. Quering, C. Wilhelm and M. Steinhilber 2012 Technology Status of Fuel Cooled Ceramic Matrix Composites for Dual-Mode Ramjet and Liquid Rocket Engine Applications (Tours: 18th AIAA) pp 1-16

[48]. TumbldeNishit and Nitin Ulmek 2018 Advanced Composite Material Used in Scramjet Engine (Int. J. of Innovations in Engg. Res. and Tech.) pp 90-92

[49]. Gautam Choubeya, Lakka Sunethab and Pandey K. M 2018 Composite materials used in Scramjet- A Review vol 5 (Elsevier) pp 1321-1326

[50]. Terence M. F. Ronald 1990 Materials for Hypersonic Engines (Madrid: Hypersonic Combined Cycle Propulsion Panel Symposium) vol 36 pp 1-4

[51]. Alvaro Francisco Santos Pivetta, David Romanelli Pinto, Giannino Ponchio Camillo, Felipe Jean da Costa and Paulo Gilberto de Paula Toror 2013 Brazilian 14-X S Hypersonic Unpowered Scramjet Aerospace Vehicle Structural Analysis at Mach Number 7 (22nd Int. Congress of Mech. Engg.)

[52]. F. Zander and R.G. Morgan 2007 Transient Heat Analysis of a Carbon Composite Scramjet Combustion Chamber (16th Australasian Fluid Mechanics Conf.) pp 1177-1181
[53]. Felipe Jean da Costa, Paulo Gilberto de Paula Toro, Tiago Cavalcanti Rolim, Giannino Ponchio Camillo, Roberto da Cunha Follador and Marco Antonio Sala Minucci 2012 Design of the Brazilian 14-X Hypersonic Aerospace Vehicle (Proc. of ENCIT 14th Brazilian Cong. of Thermal Sci. and Engg.)

[54]. Tjong and Wei Chee 2007 High Temperature Materials for Hypersonic Flight Vehicles (J. of UNSW ADFA Undergraduate Hypersonics)

[55]. S.L. Draper, D. Krause, B. Lerch, I.E. Locci, B. Doehnert, R. Nigamb, G. Dasc, P. Sickles, B. Tabernig, N. Regere and K. Rissbacher 2007 Development and evaluation of TiAl sheet structures for hypersonic applications (Elsevier) pp. 330-342

[56]. J. Steelant 2008 ATLLAS: Aero-Thermal Loaded Material Investigations for High-Speed Vehicles (Dayton: 15th AIAA Int. Space Planes and Hypersonic Systems and Technologies Conf.) 092407

[57]. M. Bouchez, F. Crampon, Bruno Le Naour, C. Wilhelmi, K. Bubenheim, M. Kuhn, B. Mainzer, J. Riccius, C. Davoine and J.F. Justin 2014 Combustor and Material Integration for high speed aircraft in the European research Program ATLLAS2 (Atlanta: 19th AIAA International Space Planes and Hypersonic Systems and Technologies Conf.) pp 1-17

[58]. Jinsheng Ma, Liwei Shen and Yongxiang He 2017 Application of Composite Materials in Engine (Mater. Sci. Advanced Composite Materials) pp 1-9

[59]. Darrel R. Tenney, W. Barry Lisagor and Sidney C. Dixon 1989 Materials and Structures for Hypersonic Vehicles vol 26 no 11 (Hampton: NASA)

[60]. Nageswara Rao Muktinutalapati 2011 Materials for Gas Turbines - An Overview Advances in Gas Turbine Technology ed Dr. Ernesto Benini (InTech) pp 293-314