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REVIEW ARTICLE

Materials for Gas Turbine Engines: Present Status, Future Trends and Indigenous Efforts

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Abstract | Gas turbine engines ingest air from the ambient atmosphere and produce power using the energy of the combustion products of the highly compressed air for generation of electricity, pumping natural gases, powering ships and propelling aircrafts. The device consists of a large number of components manufactured using atleast twenty five different alloy grades to meet the performance requirements under highly demanding operating conditions. The material selection during mechanical design of the system demands consideration of various complex damage mechanisms experienced in service. This necessitated development and production of high quality material systems. Remarkable improvement in the engine performance over the years was possible due to a continuous evolution in materials and associated technologies. The demand in the availability of the suitable materials to achieve the targeted performance of the engines yielded improved alloy systems (steel, titanium alloys and superalloys), melting practices (air melt to vacuum induction melting), wrought forming and casting technologies. Composites, intermetallic and several new material systems are also being explored and some of them are successfully inducted into the application. This paper captures the material requirements in a gas turbine engine along with global and national efforts in establishing the technologies for materials in the system.

Keywords: *Gas turbine engine, Steels, Superalloys, Titanium alloys*

1 Introduction

Gas turbine engines are used for various applications, e.g. land-based power generation, oil and gas industries, marine and aircraft propulsion, etc.[1]. However, since its invention, gas turbine engine has become the defacto power plant for propelling the aircrafts. The invention of air breathing gas turbine engine powered aircraft in 1939[2] is considered to be revolutionary for mechanical engineering design and benefitted both mass air transport as well as military application[3,4]. Since its inception, the gas turbine engine industry has experienced ever-growing demand for improved aircraft performance (higher speed, lower fuel consumption, increased range, reduced noise and reduction in NO_x and CO_2 emission, etc.), while enhancing its own safety and reliability[5,6]. Thus, the associated technologies, namely aerodynamic and mechanical design, structural integrity, lifting strategies, sensor technologies, materials, manufacturing and inspection techniques, testing and qualification methodologies for the engine components have continuously evolved. Required products were successfully designed, developed, tested and certified over the decades by leading organizations (General Electric (GE), Rolls-Royce (RR), MTU Aero engines, Honeywell Aerospace, Safran Aircraft Engines, NPO Saturn, Klimov, Pratt and Whitney, CFM International, etc.) worldwide and

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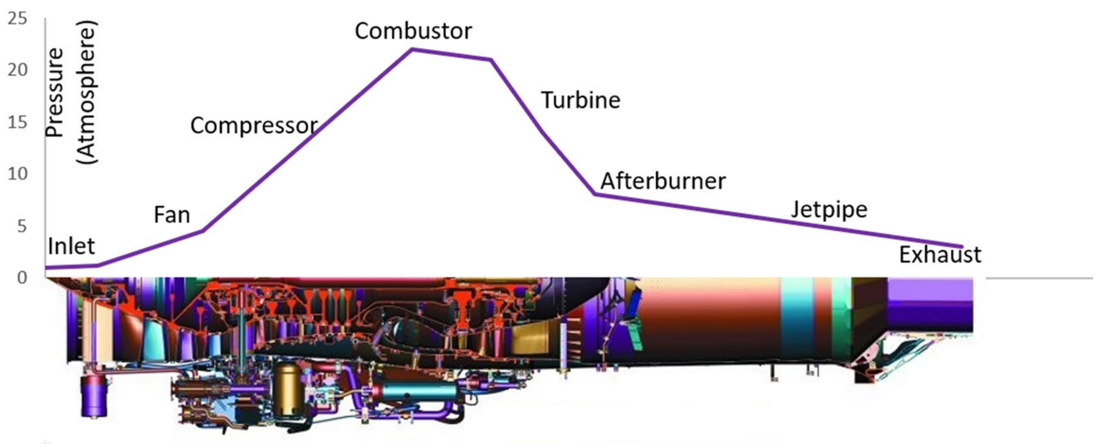

Figure 1: Typical pressure profile across the engine axis.

introduced into the service. The complex interdisciplinary knowledge required for the engine technology also necessitated understanding the future needs in advance, planning for technology roadmaps and relentless research efforts by both industry and academia. Hence continuous innovation for the targeted technologies, design, manufacturing and qualification of the components, sub-systems and systems were supported through concurrent programmes for material technology development, component development, component improvement and various technology demonstrator projects[7–10]. The contribution of materials technology is the key parameter to improve the thrust-to-weight ratio of the engine[11].

In this article, the authors capture the details of gas turbine engine architecture for aircraft application and present a review on material requirements for its components, challenges and future needs for the engine materials.

2 Gas Turbine Engines for Aircrafts

Hans von Ohain patented the concept of jet engine in 1934[12]. The same engine propelled the first jet engine aircraft by Heinkel in 1939[2] in Germany. Concurrently, Frank Whittle conceptualized a jet engine in Britain that flew a Meteor Aircraft in 1941[12]. The basic engine construction has remained the same from its conceptualization[2]. It is designed to accelerate a stream of air through the inlet, fan (low pressure compressor (LPC)) and compressor (high pressure compressor (HPC)). The fan (LPC) and compressor (HPC) modules compress the inlet gas to a high pressure with simultaneous increase in temperature as it passes through alternate stages of static and rotating blades. The hot compressed air is mixed with atomized fuel in the combustor. Temperature of the gas stream reaches the maximum level in the combustion chamber. The combustion products are directed to the turbine module to extract the thermal energy of the hot stream to drive fan and compressor. Expansion of the gas stream in the turbine also leads to lowering of pressure and temperature of gas. The hot gas stream leaves the turbine, passes though the jet pipe and nozzle and generates thrust necessary to propel an aircraft. Typical pressure and temperature profiles along the engine axis while in operation are presented in Figs. 1 and 2, respectively. The gas turbine engines in military applications additionally have afterburner module between turbine and jet pipe to generate additional thrust needed for agility and maneuver.

Rotating blades of fan, compressor and turbine are fitted to the discs and assembled on to the engine shaft/s. Such configuration rotates at a speed of 8000–20,000 revolutions per minute (rpm) to compress or expand the gas stream. Centrifugal load encountered by the blades, discs and shafts during engine operations is very high. The severity is further enhanced due to high temperature of gas stream. Gas bending loads, thermal stresses because of temperature gradient acting on these components also needs to be considered. The stationary components (stator blades and casings) also experience all these loads except centrifugal loads. These factors are considered during the material selection and design of the engine components. The operating terrains (saline atmosphere near sea, sandy air ingestion near desert, etc.) also constraints design and material choice significantly.

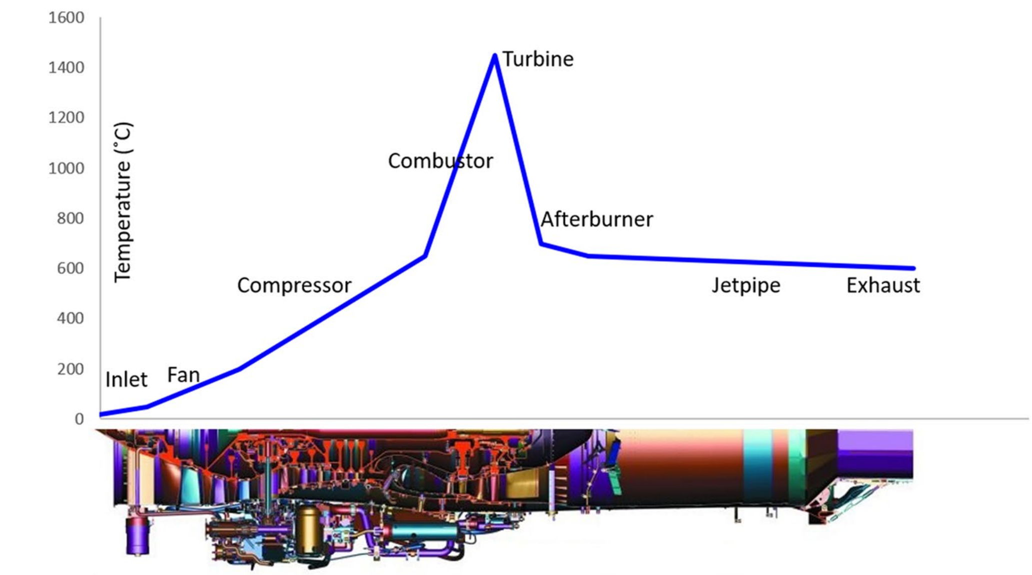

Figure 2: Typical temperature profile across the engine axis (without afterburner operation).

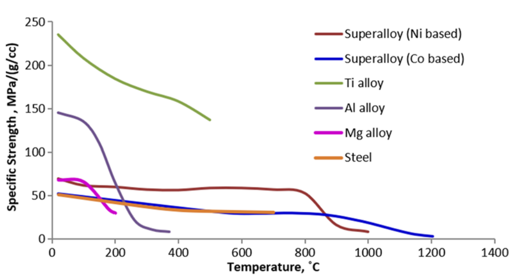

Figure 3: Comparison of specific 0.2% yield strength of different alloy systems.

3 Materials

Gas turbine engine components make use of a variety of metallic materials, composites and coating systems to meet their structural and functional requirements. Very demanding operating conditions (high temperature, stress, oxidizing and corrosive environment), weight constraint and life requirements dictate selection of materials for specific components of the engine. For military application, additional requirements like stealth impose further restrictions on the material choice. Material selection criteria are devised based on mechanical and physical properties[13] of materials, microstructural stability and functional, structural and operating condition requirements of the specific components.

3.1 Metallic Materials

Gas turbine engines in propulsion system application uses metallic materials of a wide variety, namely, steels, aluminum alloys, magnesium alloys, titanium alloys, superalloys of iron, nickel and cobalt bases[14].

Application of steels of various grades has been universal for any engineering system. The selection of alloy grades other than steel, however, is obvious for engine components and is dictated by following factors:

(a) Higher density (close to 8 g/cc) against aluminum (Al) and magnesium alloys (density near to 3 g/cc) and titanium (Ti) alloys (density near to 4.5 g/cc).
(b) Lower specific strength (0.2% yield strength/density) with increasing temperature (Fig. 3).
(c) Lesser temperature withstanding capability compared to exotic material class of superalloys.

Material evolution and new development for the jet propulsion system had been dictated by the improvement in aviation industry[6,15,16].

3.1.1 Materials for Fan and Compressor

Front side of the engine experiences low temperature compared to the rear end. Therefore, high specific strength alloys, namely Al and Ti alloys are used. Application of Al alloy is limited to static inlet guide vanes as their application is restricted to a temperature well below 200 °C[17]. Steel has been used as casing material in few engines since Ti alloy blades rotating against Ti alloy casing poses a risk of fire hazards.

Ti alloys offers the advantage of highest specific strength, low density and excellent corrosion and heat resistance properties[17–19]. The use of Ti alloys results in significant weight saving (40% against steel) and hence contributed to improved fuel efficiency and reduced noise level. Wrought Ti-6Al-4V is a workhorse aerospace material which is used for all components (rotor blades, stator blades, discs and casings) at the front end of the engine (in fan or low pressure compressor). Forged Ti 17 and Ti6246 (β Ti-alloys) are also used as fan blisk (blades integrated to disk) material[20] upto a temperature of 300 °C. Near α and α + β Ti-alloys with better elevated temperature strength (e.g. Forged Ti 685, Ti 550, TiTi6242S and Ti 834, etc.) are used for high pressure compressor components[17,20,21]. They are characterized by high strength, excellent corrosion resistance, high fracture toughness and resistance to fatigue and creep crack growth. Use of these alloys is restricted to a temperature of 500 °C.

Fan and compressor blades, discs and casings are manufactured by forging the Ti alloy feedstocks to the required shape followed by machining. The intermediate casing in between the fan and compressor section is constructed using Ti-6Al-4V material generally through casting process.

Blisk was introduced into service for high thrust-to-weight ratio military engine applications (e.g. GE F120[22], F414[22], EJ 200[22], PW600[22], F136[7], GE 129EFE[23]) and passenger aircrafts. The manufacturing options are milling from a solid pancake, electrochemical machining or joining finished forged-aerofoils to the disc by Linear Friction Welding (LFW) process. Further advancement towards disc application is reported as use of bladed ring (bling) made out of titanium matrix composites yielding about 70% weight gain[17]. γ Titanium–Aluminum-based intermetallics are another class of promising materials for rear stages of compressor rotor and stator blades[20].

Present research on development of new Ti alloys is concentrated on hollow light weight Ti fan systems (large blades of civil aero-engines[2], F136[7]), Ti alloy bladed disc (blisk) and burnt resistant Ti alloys to replace heavier Ni-base superalloys.

Rear stages of compressor, where operating temperature exceeds 500 °C, Nickel (Ni)-based superalloy is used. IN 718 is the commonly used alloy for such application[24].

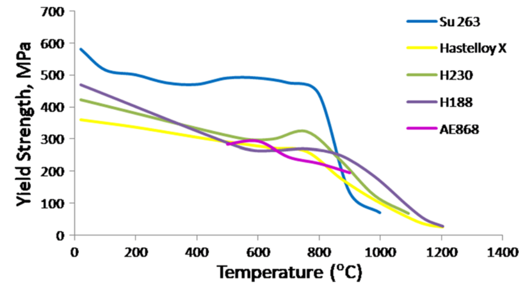

Figure 4: Strength of various superalloys in combustor and afterburner application.

3.1.2 Materials for Combustor and Afterburner

Both these modules require materials which can withstand high temperatures for long duration. The metal temperature of the combustor liner and after burner parts exceeds 1000 °C. Hence heat resistant superalloys are used for fabrication of combustor and afterburner components[24]. Su 263, a Ni-based super alloy in sheet metal form is used as the liner material for both combustor and afterburner. H 188, Hastelloy X, H230, AE868 are few other Ni- and Co-based super alloys used in this application[2]. A comparative study based (Fig. 4) on the open literature reveal that Haynes 188, Hastelloy X and Haynes 230 can withstand much higher temperature compared to C 263[2,25]. Combustor and afterburner casings are fabricated from IN 718 forgings[26]. Ti alloys are used as outer casing of the jet pipe[26].

3.1.3 Materials for Turbine

The performance of the aero-gas turbine engines has been closely related to the development of improved superalloy systems[27]. The early Ni–Cr–Fe solid solution wrought superalloys were replaced by a cast Co-based superalloy Vitallium (Co-27Cr-5.5Mo-2.5Ni-0.25C) in 1942 to overcome forgeability issues[28]. This work led to the successful manufacture of investment cast components for the first production gas turbine engine in 1945. Nickel-based alloys gained importance simultaneously as the addition of Al and Ti to the system was found beneficial with respect to the tensile strength at elevated temperature due to precipitation hardening effect[29]. Cast Ni-based alloy development superseded Co-based alloy development work by 1950 because of the shortage of Co supply and more importantly due to their superior strengthening potential by stable and coherent γ'precipitates.

The efficiency of a gas turbine engine is dictated by the turbine entry temperature (TET) [27].

Higher the TET is, greater is the efficiency. TET is rightly called the "Metallurgical Limit" as this temperature is limited by the highest temperature capabilities of the available materials. Ever increasing need for higher TET[30] necessitated the development of the investment casting processes with complex cooling passages as well as new alloy systems for turbine blades and nozzle guide vanes[31]. The material for the turbine rotor blades and vanes (static nozzle guide vanes) thus has changed from the polycrystalline materials to directionally solidified (DS) alloys of different generations followed by single crystals (SX) of up to sixth generation alloys[32].

The development of directionally solidified (DS) alloys has resulted in low modulus (100)-oriented columnar grains aligned radially and exhibited significant improvements in creep strength, ductility and thermal fatigue resistance. The ultimate goal to eliminate grain boundaries led to development of single-crystal (SX) materials[33]. Elimination of grain boundaries in SX material improved creep resistance considerably and hence enhancement in turbine entry temperature (TET) and prolonged service duration could be realized[33].

A number of alloys were developed by the established engine houses like GE, Pratt & Whitney, Rolls-Royce and Snecma. Early development of single-crystal superalloys[34] included PWA 1480, Rene N4, SRR 99, RR 2000[35], AM1[36], CMSX2[37], CMSX3[37] and CMSX6[37]. These alloys have near similar creep rupture strength but different cast-ability, solution treatment windows and propensities for recrystallization upon solution treatment, environmental oxidation properties, hot corrosion properties and densities[37]. MARM 200Hf, Rene 80H, MARM 002 and MARM 247 were a few first-generation DS superalloy with extensive turbine engine aerofoil application[30,33]. Second generation DS and SX superalloys include CM247LC (DS) and PWA 1484 (SX) and CMSX4 (SX). Early problem of grain boundary cracking in MARM 200 was resolved by adding Hafnium. Third generation SX blade materials (CMSX 10, Rene N6) were developed with increased rhenium (Re) content (up to 6% against maximum of 3% in second generation alloy). Addition of ruthenium replacing Re resulted in the development of 4th generation SX blade material (MCNG[38], TMS 138 and TMS 162[39].

Turbine discs experience different service conditions across the component ranging from relatively high stresses and lower temperatures (around 300 °C) at the bore to higher temperatures (around 650 °C) and lower stresses at the rim. Stress concentration features such as fir tree root fixings at the rim further increase the need for excellent high temperature damage tolerance in view of the cyclic loading experienced by these components. Most turbine discs are now manufactured from nickel-based superalloys due to their good resistance against combinations of fatigue, creep, oxidation and corrosion damage[3,40,41]. Typical such alloys are IN 718, Directly Aged IN 718, Udimet 720, Udimet 720Li, Rene 95, RR1000, Waspaloy, ME3, etc. Powder metallurgy (PM) disc alloys[42] such as Rene 88 DT (GE CF6, GE 90-90B, GE F414), Rene 104 (GP7200), Astroloy, N18[35], N19[41] were developed to get the best balance between tensile strength, creep resistance and damage tolerance for the disc application. The powder metallurgy route[41] (powder processing, extrusion and forging) resulted processing of larger sized disks of superalloys with higher precipitation content and/or with higher content of refractory metals (Mo, W, Nb, Ta). Chemical segregations in the disk were minimized. This resulted in uniform deformability of the PM billet during forging of disks of highly strengthened superalloys[41]. Though, PM discs have homogenous structure and superior strength compared to cast and wrought alloys, however, their production costs are higher[43].

Development efforts towards 'dual microstructure' have also been reported in the disc application that allowed the rim and hub of the disk to be individually optimized[42]. The rim is creep limited and is treated to produce a coarse grain size, whereas the hub is fatigue limited and requires a fine grain size. Dual microstructure disks have been tested and verified through both coupon tests as well as disk spin testing.

Casings for turbine section are also fabricated using ring forgings of Ni-based superalloy[26].

3.1.4 Materials for Accessory Systems (Gear Box, Lubrication and Bearings)

Aluminum (Al) and Magnesium (Mg) alloys have advantage of lower density and hence they are preferred where strength and temperature capabilities meet the operating conditions of the engine[4,11]. Gear box casing is one component, where cast Al and Mg alloys are utilized worldwide. Gears are manufactured using case hardening grade alloy steels[14]. A number of bearings are used in the gas turbine engines for providing support to shafts during rotation.

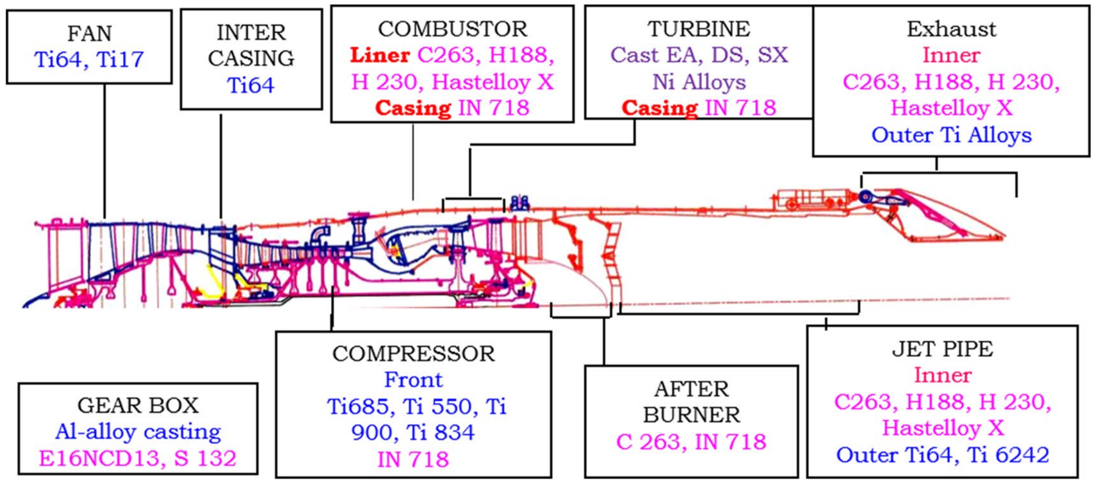

Figure 5: Module-wise alloy system used for engine components.

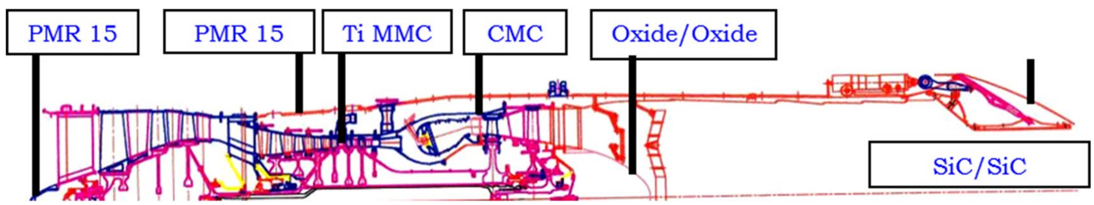

Figure 6: Possible use of composites in gas turbine engine components.

Both axial and radial load carrying bearings are in use for this purpose. High strength steels are used in bearings application[14]. The pipelines for the oil and fuel systems are manufactured from steel or titanium tubes[14].

Figure 5 summarizes the material systems used in various modules of the gas turbine engine.

3.2 Composites

Composites offer the advantage of higher operating temperature and high specific strength, improved performance, and thus enable efficiency. Due to these characteristics, there has been significant interest in composite materials for military and commercial engines[7,44–46]. Various combinations of matrix and reinforcement elements are in use in gas turbine engines[47]. They are.

(a) Polymer matrix composites (PMC).
(b) Metal matrix composites (MMC).
(c) Ceramic matrix composites (CMC).

PMCs are targeted for front end of the components and bypass duct as it can withstand relatively lower temperature (200 °C)[7,36]. Design, development, fabrication and testing of engine inlet housing were completed using carbon fiber in PMR 15 resin as part of the Integrated High Performance Turbine Engine Technology (IHPTET) Initiative[7]. Carbon Fiber Reinforced Plastic composite (CFRP) blades with titanium leading edge (Ti-6Al-4V alloy) were introduced in the GE90 engine for improving the impact damage resistance in case of bird strikes[2].

CMCs on the other hand can withstand extremely high temperature (above 1100 °C)[15,47]. Hot end components of engine (turbine shroud segment[47], exhaust cone [[47]], flaps [[36]], etc.) are possible targeted application of CMC engine parts. Oxides, Carbon and SiC-based CMCs are established in such application[36,47].

Ti-MMCs are also being considered for compressor bling (bladed ring) which can replace bladed disk or blisk[47]. Possible use of composites in gas turbine engine application is presented in Fig. 6.

3.3 Coatings

Harsh operating condition in a gas turbine engine demands application of coatings on various components to enhance their durability and to maximize the exploitation of the properties of the used materials[48–50]. Typically, these coatings are aimed at modifying the surface properties of critical components to provide enhanced resistance against deterioration due to mechanisms such as corrosion, oxidation, wear, or base metal exposed to high temperature. In recent years, considerable advances in the field of coatings technology have accompanied the growing realization of the immense potential of surface engineering in the modern industrial world. Consequently, a number of methods are now available for developing a wide variety of protective coatings.

In the front part of the engine, including the fan and the compressor, the abrasion and erosion resistant coatings and seals are typically employed[48]. However, in the hot section of the engine, which includes the combustion chamber area, turbine, after burner flame holder, the thermal barrier coatings (TBCs) and high-temperature wear resistant seal coatings are used[48].

Modern engine constructions together with the technological advancement led to the evolution of new coating types and to the improvement of the formerly used coatings[49,50]. The most remarkable one being the high strain tolerant low thermal conductivity Electron Beam Physical Vapour Deposition (EBPVD) TBC for turbine blade and nozzle guide vane application. Apart from regularly used yttria stabilized zirconia (YSZ), development of Ceria stabilized zirconia (CeSZ), rare-earth zirconates (e.g. $La2Zr2O_7$, $Gd2Zr2O_7$, $Sm2Zr2O_7$) as potential TBC system are reported[50]. Furthermore, oxidation resistant coatings are under development improving significantly the oxidation behavior of TiAl above 900 °C[50].

4 Recent Advancement and Present Research Trends

Material evolution and new development for the jet propulsion system had been dictated by the improvement in aviation industry[15,16]. The performance parameters for the gas turbine engines improved significantly and hence design, manufacturing and material technologies also gained advancement. Improvement in material systems and growth in material technologies for gas turbine engine industry had been significant. Improved melting practices for raw materials, wrought alloy processing technologies, evolution in casting technologies are briefly discussed in previous sections. Some more alloy systems, which are in existence for quite some time, is being considered for using in the engine application as they possess properties that meet the requirements of the engine operating condition. Few such systems are mentioned in subsequent sections.

4.1 Intermetallics

Another class of developing materials, intermetallic alloys offer strength, temperature endurance and weight advantages over current materials. Titanium aluminides (TiAl and Ti_3Al) are useful at higher temperatures (750 °C) and offer substantial weight savings over pure titanium or nickel-based alloys, making them good candidates for combustor cases, compressor blades at the rear (highest pressure and temperature) stages[20,51,52]. Few engine houses have reported successful testing of the cast γ TiAl intermetallic (LP turbine blades at GEAE (CF6 engine) with a successful bench testing, HP compressor blades and shrouds in the US CAESAR program (RR, Allison AADC, GE, PW), Blade retainers (PW), Turbine dampers (Volvo), LPT blades (MTU)). Snecma and Turbomeca made several demonstrations of feasibility using various processes (foundry, extrusion, forging, powder metallurgy[53]). Nickel aluminides also have potential application as turbine nozzle guide vanes with oxidation resistant protective coating[54]. IC6 Ni_3Al-based alloy with NiCrAlYSi has been tested in PD14 prototype (a next generation turbofan engine which may become one of the alternative power source for the Ilyushin Il-76 and Irkut MS-21 twin-jet passenger aircraft).

4.2 High Entropy Alloys

High entropy alloys (HEAs) are materials with complex compositions of multiple elements. Their high configuration entropy mixing is more stable at elevated temperatures[55]. Refractory metal HEAs containing Nb, W, Mo, Ta, etc. are reported to retain useful strength upto 1700 °C. This attribute allows suitable alloying elements to increase the properties of the materials based on four core effects (high mixing entropy effect, sluggish diffusion effect, lattice distortion effect and the cocktail effect), which gives tremendous possibilities as potential structural materials in jet engine applications. Potential engine components are structural casings (midframe and exhaust casing), nozzle and exhaust cone[56]. Service temperature for these components varies in the range of 300–1000 °C.

4.2.1 DSE Alloys

Directionally solidified eutectic (DSE) ceramics add new potentialities to the advantages of sintered ceramics: a higher strength, almost constant up to temperatures close to the melting point, and a better creep resistance. In the domain of structural materials for very high temperature applications, the use of DSE oxides is envisaged for a new generation of gas turbines operating with turbine inlet temperatures as high as 1700 °C. The applications could be vanes, hollow non-cooled nozzles, eventually, turbine blades and, in the combustion chamber, liner panels, etc.[57].

4.3 Refractory Metal Silicides

The development of new gas turbine hot section materials with increased high temperature capabilities is crucial for the design of future efficient turbines with low CO_2 and NOx emission levels. Refractory metal silicides and nitride-based ceramics combine the properties of higher temperature capability and low density, which may lead to substantial reductions in aircraft fuel consumption. Niobium silicide-based alloys and silicon nitride/molybdenum disilicide composites are currently being developed for turbine hot section components for both aircraft engines and land-based turbines[58].

4.4 Transpiration Materials for Combustion Chambers

Onera[59] has designed and characterized porous materials obtained by means of additive manufacturing. The targeted application is the replacement of the multi-perforated walls of combustion chambers. Aero-thermal tests have demonstrated improved cooling efficiency at the leading-edge of combustor. The prospects may involve producing materials via LBM (Laser Beam Melting), with the advantage of greater finesse in the porous architectures generating more efficient cooling.

4.5 Additively Manufactured Components

Additive manufacturing process has gained tremendous thrust in recent past in every sector. Aerospace industry also has embraced this technology for manufacturing of complex and critical components which is difficult to produce through conventional routes or requires assembly of multiple components[59,60]. Fuel atomizer body in the engine combustor is one important component that is realized using this technique and put into service. Recent research initiatives are reported for various other engine components that include compressor and turbine blades.

5 Global Development Efforts for Materials and Material Technologies

Several programmes were launched by USA, Canada and European countries to improve the engine performance and efficiency of engines[61,62]. China and Japan also launched such initiatives and joined consortiums for collaborative developments. Many of these programmes have resulted in development of materials or forms (e.g. blisks, blings, SX). Few reported programmes, along with their objective and material information are listed in Table 1[7–10,30,34].

6 National Scenario

Gas Turbine Research Establishment (GTRE) is involved in design and development of gas turbine engine for the military aircraft application. Significant progress is made with the design and development of Kaveri Engine which is a low bypass twin spool turbo fan engine of 80 kN thrust class (Fig. 7).

Defence laboratories, namely, Defence Metallurgical Research Laboratory (DMRL), Defence Materials and Stores Research and Development Establishment (DMSRDE) are pioneering the research in the field of materials and forms in propulsion system application in country. Research laboratories under Centre for Scientific and Industrial Research (CSIR) are also making significant contribution in raw material development and component manufacturing technique. Considerable number of alloy systems (steels, titanium alloys, aluminum alloys and superalloys) has been indigenized with airworthiness approval from the certification agency (CEMILAC)[26]. Raw materials (bars, sheets, forging and casting feedstocks) are produced by Mishra Dhatu Nigam (MIDHANI) and few other private agencies. Forgings are developed by Hindustan Aeronautic Limited (HAL), Bharat Forge Limited (BFL), Steel and Industrial Forging Limited (SIFL) and MIDHANI. Critical casting technologies for turbine blades and nozzle guide vanes have been established by DMRL and technology for productionization was transferred to HAL. PTC has developed titanium casting facility.

Requirements for new alloy, raw parts (bar, forging feedstock, sheet, plate, casting feedstock, etc.) and component development along with certification is the key in successful design and development of high thrust class engines. Development of new materials and establishment of complex material processing technologies gained momentum through extensive academia-R&D laboratories collaborations.

Table 1 Global programmes on jet engine technology enhancement

Sl. No	Programme name	Objective	Materials/forms developed/used
1.	IHPTET: Integrated High Performance Turbine Engine Technology[8]	Improved engine performance	PMC PMR 15[7] SX turbine blades and vanes CMC inner liner of combustor CMC nozzle flap Organic matrix Composite (OMC) nozzle outer skin and cooling supply tube[8] MMC Intermetallic[63]
2.	CIP: Component improvement programs[9]	Product improvement leading to improvement in engine performance, reduced development cost, and improvement in reliability and maintainability	Ti alloy compressor blades Cast turbine blades Discs
3.	ADVENT: Adaptive Versatile Engine Technology (GE and RR)[64, 65]	Development of engine optimized for several operational conditions Three-stage, variable-geometry adaptive fan Large annular duct to accommodate the third stream Very high-pressure ratio compressor (LEAP engine concept)	Fan blisks Polymer matrix composite SX TBC PM discs Ceramic matrix composite
4.	HEETE: Highly Efficient Embedded Turbine Engine[66, 67]	Reduced fuel burn through very high-pressure ratio Technology for next generation compressor Reduction in SFC, CO_2 emissions	Polymer matrix composite SX Ceramic matrix composite
5.	AATE: Advanced affordable Turbine Engine[65]	Demonstrator (4-year programme) Reduced SFC Reduced cost	Fan blisks Polymer matrix composite SX TBC PM discs CMC
6.	VAATE: Versatile Affordable Advanced Turbine Engines[65, 68]	Efficient, high-overall-pressure-ratio compression systems Variable-cycle engine technologies Advanced high-temperature materials and more effective turbine blade cooling Techniques to more efficiently recuperate energy while satisfying thermal and power requirements	Fan blisks Polymer matrix composite SX PM discs TBC Ceramic matrix composite
7.	AETP: Adaptive Engine Technology Programme or ACE: Adaptive Cycle Engine (vary their bypass ratios for optimum efficiency at any combination of speed and altitude)[63]	Increased combat aircraft thrust Improved fuel consumption Extended range Significantly more aircraft heat dissipation capacity	Fan blisks PMC SX PM discs TBC CMC
8.	NEWAC: New Aero Engine Core Concepts[60]	Reduced fuel burn and emissions by improving thermal efficiency Developing lean combustion technology Intercooling Intercooling with recuperation Improved high pressure (HP) compressor aero design and blade tip rub management 'Aspirated' compression systems Active control of surge and tip clearance in compressors Active control of a cooling air system Ultra-high OPR core with intercooling Medium OPR intercooled recuperated core High OPR flow-controlled core	A new abradable coating has been developed, to improve the incursion cutting behavior (blade wear and transfer) and corrosion resistance. The new coating has been validated by incursion tests and corrosion tests (salt spray)[69] Additively manufactured cross-flow cross-corrugated heat exchanger γ Ti–Al aluminide for HP compressor and LPT

Table 1 (continued)

Sl. No	Programme name	Objective	Materials/forms developed/used
9.	Clean I and Clean II[10]	Reduction in fuel burn Reduction in NOx emissions	Additive manufacturing of perforated combustor liner CMC shroud segment EBPVD TBC Coating on turbine aerofoil
10.	ULTMAT (Ultra High Temperature Materials for Turbines)[70]	Introduction of innovative materials, viz. Mo- and Nb-silicide-based multiphase alloys, with enhanced high temperature capabilities (100 °C to 150 °C advantage) compared to presently used Ni-base single-crystal superalloys, for application in aircraft/rotorcraft engines and in aero-derivative land-based gas turbines[69]	Mo-silicide-based alloy composition that provides reasonable mechanical properties and oxidation resistance; could be used in static turbo-engine components Nb-silicide-based alloy compositions for blades
11.	HYPR (Super/Hyper- Sonic Transport Propulsion System)[71]	Development of Super/Hyper-Sonic Transport Propulsion System	SX PMC CMC
12.	ESPR (Research and Development of Environmentally Compatible Propulsion System for Next Generation Supersonic Transport Project)[70]	Development of environmentally compatible propulsion system for next generation supersonic transport project	SX PMC CMC

Figure 7: Indigenously developed Kaveri Engine.

Aeronautical Research and Development Board (ARDB) initiatives, Gas Turbine Enabling Technologies (GATET) and Centre of Propulsion Technologies (CoPT) are major contributors for nation's research thrust in the gas turbine engine technologies. A recent ARDB program named "Gas Turbine Materials and Processes" (GTMAP) was conceptualized in collaboration with GTRE-DMRL-Academic Institute to meet the future propulsion systems requirements for materials and related systems. A number of projects for structural materials, lifing technologies, coatings, sensors, manufacturing technologies have been taken up. Apart from this, GTRE is continuously engaging the academic institutions for goal-oriented programmes on characterization techniques of materials, processing of components through Contracts for Acquisition of Research Services (CARS) and Extramural Research and Intellectual Property Rights (ER and IPR) programmes. Such initiatives are found to be tremendously effective in establishing confidence in the ongoing engine programmes in the country. A contemporary approach for integrated computation materials engineering (ICME) is also paving way for the significant reduction in time and effort for new material development in the country.

7 Concluding Remarks

The turbo-machinery design concept in the gas turbine engine application is experiencing continuous evolution and hence the associated materials and material processing technologies. The advanced combat aircraft engine also demands high survivability, low observability, integrated thermal and power management and better operating envelope. Key technology differentiators could be compact, high pressure ratio core engine, use for high temperature light weight composites with long endurance, blisk and bling technologies, intermetallics, etc. Sustained research effort by the engine houses and academic fraternity achieved the desired design methodologies and established technologies for ever increasing requirements of aviation industry.

Abbreviations

BPR: By-pass ratio; CMC: Ceramic matrix composite; DS: Directionally solidified; DSE: Directionally solidified eutectic; EBPVD: Electron beam physical vapour deposition; HEA: High entropy alloys; HPC: High pressure compressor; LPT: Low pressure turbine; MMC: Metallic matrix composite; OPR: Overall pressure ratio; PM: Powder metallurgy; PMC: Polymer matrix composite; PVD: Physical vapour deposition; SX: Single crystal; TBC: Thermal barrier coating; TET: Turbine entry temperature.

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Declarations

Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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References

1. Harman RTC (1981) Applications for Gas Turbine Engines. In: Gas Turbine Engineering. Palgrave, London. https://doi.org/10.1007/978-1-349-16484-4_2
2. Okura T (2015) Materials for aircraft engine. ASEN 5063 Aircraft Propulsion Final Report
3. *Advanced High Temperature Materials: Aeroengine Fatigue.* M. R. Winstone, J. W. Brooks. 1/2, 2008, High Temperature Fatigue, Ciência e Tecnologia dos Materiais, Vol. 20.
4. Liu H, Zhang S, Liang C, Liu Q (2015) Development strategy study for commercial aero engine companies in european countries and United States. Proced Eng 99:804–811
5. Kyprianidis K (2011) Future Aero Engine Design: An Evolving Vision. Ernesto B (Ed.). Gas Turbine Technol, pp. 3–24.
6. International Air Transport Association (2009) Aircraft technology roadmap to 2050. International Air Transport Association, Geneva
7. Hoff S (1994) Engine cold section materials application. SAE Technical Paper 941222. https://doi.org/10.4271/941222
8. First Full Scale Engine Evaluation of an IHPTET Exhaust Nozzle Technology Demonstrator (1995) 31st AIAA/ASME/SAE/ASEE joint propulsion conference and exhibit
9. Shishko R (1973) Technological change through product improvement in aircraft turbine engines. United States air force project rand. R-1061-PR
10. Honeywell Cleen II (2017) 21-15790(03)-2
11. AGARD Advisory Report 308 (1992) Propulsion and energetics panel working group 20 on test cases for engine life assessment technology
12. Banerjee D (2007) Materials in flight. Prof. Brahm Prakash Memorial Lecture, 23 in series
13. Lagow BW (2016) Materials selection in gas turbine engine design and the role of low thermal expansion materials. Lagow, Benjamin W. 11, JOM, Vol. 68
14. Rolls R (1996) The jet engine. 5th. ISBN 0 902121 2 35
15. Krishan LL (2021) Ceramic matrix composites (CMCs) for gas turbine applications. GE corporate research and development, schenectady, NY 12301, funded by DOE under Contract No. DE-FC02-92CE410000
16. Smith DJ (2013) 'Power-by-the-hour': the role of technology in re-shaping business strategy at rolls-royce. Technol Anal Strateg Manag 25:987–1007. https://doi.org/10.1080/09537325.2013.823147
17. Whittaker M (2011) Titanium in the gas turbine engine
18. Ikuhiro I, Yoshihisa S (2014) Application and features of titanium for the aerospace industry. Nippon Steel and Sumitomo Metal Technical Report No. 106
19. Esslinger J (1960) Titanium in aero engines. MTU Aero Engines, Germany
20. Williams JC, Boyer RR (2020) Opportunities and issues in the application of titanium alloys for aerospace components. Metals 10:705
21. Gogia AK (2005) High-temperature titanium alloys. Def Sci J 55:149–273
22. Fu Y, Gao H, Wang X et al (2017) Machining the integral impeller and blisk of aero-engines: a review of surface finishing and strengthening technologies. Chin J Mech Eng 30:528–543. https://doi.org/10.1007/s10033-017-0123-3
23. Wadia AR (2000) F110-GE-129 EFE—enhanced power through low risk derivative technology
24. Hagel WC, Sims CT (eds) (1972) The superalloys. Wiley, New York
25. International H (1996) Haynes data sheet on respective alloys

26. Subrata D, Narendra BSN, Ghosh SN (2004) Air breathing engines and aerospace propulsion: proceedings of NCABE. Advances in materials for kaveri engine programme
27. Reed RC (2006) The superalloys, fundamentals and application. Cambridge University Press, Cambridge
28. Ericson GL (1990) Polycrystalline Cast Superalloys. ASM international handbook committee. Prop Sel Irons Steels High Perform Alloys 1: 981–994 (Cannon-Muskegon Corporation)
29. Anton DL (2000) Ni3Al in nickel-based superalloys. Fleischer RL, Westbrook JH (Eds.). Structural applications of intermetallic compounds. Wiley, New York
30. Das N (2010) Advances in nickel-based cast superalloys. Transactions of the indian institute of metals, vol. 63. Springer, Berlin, pp. 265–274
31. Pierre C, Tasadduq K (1999) Evolution of Ni-based superalloys for single crystal gas turbine blade applications. Aerosp Sci Technol 3:513–523
32. Versnyder FL, Shank ME (1970) The development of columnar grain and single crystal high temperature materials through directional solidification. Mater Sci Eng A 6:213–247
33. Harris K, Erickson GL, Schwe RE (1990) Directionally Solidified and Single-Crystal Superalloys. ASM international handbook committee. Properties and selection: irons, steels, and high performance alloys, ASM handbook, Vol. 1. Cannon-Muskegon Corporation, Muskegon, pp. 995–1006
34. Khan P, Caron T (1999) Evolution of Ni-based superalloys for single crystal gas turbine blade applications. Aerosp Sci Technol 3:513–523
35. Ford DA, Arthey RP (1986) Development of single crystal alloys for specific engine applicatons. Rolls-Royce Ltd., London
36. J Christophe Corde (1990) SNECMA M88 engine development status. Proceedings of The American society of mechanical engineers, presented at the gas turbine and Aeroengine congress and exposition—June 11–14, Brussels, Belgium
37. Kamaraj M (2003) Rafting in single crystal nickel-base superalloys—an overview. Sadhana 28:115–128
38. Caron P, James A, Gabb T, McLean M, Harada H (Eds.) (2003) French developments of Superalloys for gas turbine disks and blades. The minerals, metals and materials society. Fuchs G, TMS, 2003. Advanced Materials and Processes for Gas Turbine, pp. 17–27
39. Nakagawa Y (2004) Aero-engine business and material technologies in Japan. Superalloys
40. Pollock TM, Tin S (2006) Nickel-based superalloys for advanced turbine engines: chemistry, microstructure, and properties. J Propuls Power 22:361–374
41. Fecht D, Furrer H (1999) Ni-based superalloys for turbine discs. JOM 51:14–17
42. Caron D, Locq P (2011) On some Advanced nickel-Based Superalloys for Disk Applications. AerospaceLab Onera J
43. Nishikiori S, Takahashi S (2003) Development of turbine disc materials for aircraft engines. Proceedings of the International Gas Turbine Congress
44. MTU Aero Engines. Next engine generation: materials, surface technology, Manufacturing processes
45. Campbel FC (2010) Structural composite materials. Materials Park, ASM International
46. Kumpfert J, Peters M, Kaysser WA (1999) The potential of advanced materials on structural design of future aircraft engines. DLR-German Aerospace Centre, Institute of Materials Reseach, Germany
47. Klaus S, Hans W (2000) Next engine generation: materials, surface technology, manufacturing processes: what comes after. MTU Aero Engine
48. Klaus S, Hans W (2000) Next engine generation: materials, surface technology, manufacturing processes: Ehat comes after. MTU Aero Engine
49. Schilke PW (2004) Advanced gas tubine materials and coatings. GE Energy. GER-3569G (08/04)
50. Leyens, C (2014) Advanced materials and coatings for future gas turbine application. 24th international congress of the aeronautical sciences
51. Postans PJ, Cope MT, Moorhouse S, Thankker AB (1993) Applications of Ti Aluminides in gas turbine engine components. The minerals, metals and materials society. Froes FH, Caplan I (Eds.). Science and Technology, Titanium 92
52. Kunal K, Radhakrishnan R, Wereley NM (2012) Advances in in gamma titanium aluminides and their manufacturing techniques. Vol. 55, Progress in Aerospace Sciences, pp. 1–16
53. Lasalmonie A (2006) Intermetallics: why is it so difficult to introduce them in gas turbine engines? Intermetallics 14: 1123–1129
54. Jozwik P, Polkowski W, Bojar Z (2015) Applications of Ni3Al based intermetallic alloys—current stage and potential perceptivities. Materials 8:2537–2568
55. Senkov DB, Miracle ON (2017) A critical review of high entropy alloys and related concepts. Acta Mater 122:448–511
56. Modupeola D, Patricia P, Samson A, Ntombi M (Eds.) (2019) High entropy alloys for aerospace applications. Intech Open. Advanced Materials for Aerospace Application
57. Parlier M, Valle R, Perrière L, Lartigue-Korinek S, Mazerolles L (2011) Potential of directionally solidified eutectic ceramics for high temperature applications. Onera J Aerosp Lab 3:1
58. Justin S, Drawin JF (2011) Advanced lightweight silicide and nitride based materials for turbo-engine applications. The Onera J Aerosp Lab
59. Onera (2019) Onera annual report
60. Kuan Tan JH, Leong Sing S, Yee Yeong W (2020) Microstructure modelling for metallic additive manufacturing: a review. Virtual Phys Prototyp 15(1):87–105. https://doi.org/10.1080/17452759.2019.1677345

61. National Security and International Affairs Division (1989) Research and development funding of jet aircraft engine for fiscal years 1984–1989
62. Hong WS, Collopy PD (2005) Technology for jet engines: case study in science and technology development. J Propuls Power 21:769–777
63. Younossi O, Arena MV, Moore RM, Lorell M, Mason J (2002) Military jet engine acquisition: technology basics and cost-estimating methodology. Rand Corp Santa Monica Ca
64. https://en.wikipedia.org/wiki/Adaptive_Versatile_Engine_Technology
65. Engines of Innovation—Air Force Magazine (2017) Air Force Magazin
66. https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2010/SET/Thomson.pdf. 11th Annual Science and Engineering Technology Conference/DoD Tech Expo
67. GE Aviation entering new propulsion era with multiple R&D programs, https://www.airframer.com/news_story.html?release=4106
68. American Institute of Aeronautics and Astronautics (2006) AIAA Air Breathing Propulsion Technical Committee. The versatile affordable advanced turbine engine (VAATE) initiative
69. NEWAC Technologies, Highly Innovative Technologies for Future Aero Engines (2011)
70. Ultra High Temperature Materials for Turbines (2008) Final activity report, european framework programme FP6—Specific targeted research project (STREP)
71. Nakagawa Y, Pollock TM, Harada H, Howson TE, Reed RC, Schirra JJ, Waltson S, Green KA (2004) Aero-engine business and material technologies in Japan. TMS (The Minerals, Metals & Materials Society, Warrendale, pp 3–12

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