Use of Ceramic Matrix Composites (CMCs) in High-Pressure Turbine of the Jet Engine

Keval Babu

Independent Researcher
Texas, USA

Abstract

The jet engine has been pivotal in both war and peace, propelling humanity to new heights and broadening our horizons. However, the environmental impact of fuel combustion in predominant transportation modes, like air travel, has become a growing concern due to climate change. This paper investigates how the integration of Ceramic Matrix Composites (CMCs) into the high-pressure turbine of jet engines can significantly enhance engine efficiency, reduce emissions, and lower fuel costs. It begins by outlining the fundamental principles and performance requirements of jet engines, followed by an examination of material trends and the selection process for alternative materials. The properties and manufacturing process of Silicon Carbide/Silicon Carbide (SiC/SiC) CMCs are discussed in detail. The concluding sections address the challenges associated with recycling CMCs, evaluate their benefits, and provide insights into the future applications of SiC/SiC CMCs in jet engines.

Keywords: CMC, SiC/SiC, HP, LP, LEAP, CFM, GE, LSI

Introduction

The jet has served as both an instrument of war and a beacon of peace. It has carried humanity to the brink of space and provided us with the means to explore our diverse planet, making our horizons truly global. This remarkable journey has been made possible through the continuous development and enhancement of the jet engine. Predominant modes of transportation, including air travel, rely on fuel combustion to power engines, which in turn emits substantial amounts of harmful pollutants. In the realm of transportation, the growing awareness of environmental impact due to climate change has spurred a shift towards sustainability.

Additionally, the rise in oil prices has emphasized the need for alternative, more cost-effective technologies. Currently, a significant trend in the aviation industry is the development of more efficient engine technologies aimed at reducing emissions and lowering fuel costs. This paper explores how integrating Ceramic Matrix Composites (CMCs) into the high-pressure turbine of jet engines can lead to revolutionary improvements in engine efficiency.

The paper begins by detailing the fundamental principles and performance requirements of jet engines. It then examines material trends, the process of selecting alternative materials, and the properties and manufacturing process of Silicon Carbide/Silicon Carbide (SiC/SiC) CMCs. In the concluding sections, it addresses the challenges associated with recycling CMCs, evaluates the benefits of their use, and provides insights into the future of SiC/SiC CMC applications in jet engines.

Background

To understand how efficiency improvements can be achieved in a jet engine, it is essential to grasp the basic working principles of a jet engine. The high bypass ratio turbofan is the most common type of jet engine used in modern aircraft. It consists of a fan, a low-pressure compressor and turbine, a combustion chamber, and a high-pressure compressor and turbine as shown in Figure 1 below.

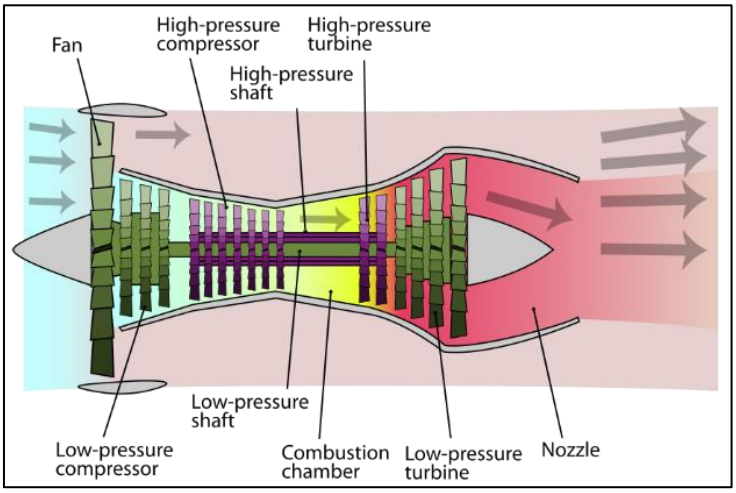

Figure 1: Depiction of high by-pass turbofan engine[1]

The operation of a jet engine can be broken down into four fundamental steps [1]:

1. **Suck**: Air is drawn in through the large front fan, with the majority directed around the engine as pure thrust. The front fan generates 75% of the engine's thrust [2].
2. **Squeeze**: The remaining air enters the engine's core and is compressed through a series of low and high-pressure compressors. The air is compressed to the required pressure and temperature for combustion.
3. **Bang**: In the combustion chamber, the compressed air is mixed with fuel and ignited, raising the pressure and temperature of the air. The explosive expansion of hot air propels it towards the rear of the engine, creating the remaining 25% of thrust.
4. **Blow**: Before exiting the engine, the high and low-pressure turbines extract energy from the exhaust air to drive the fan and the low and high-pressure compressors.

Performance Requirements

Jet engines must exhibit high efficiency, low weight, an optimal thrust-to-weight ratio, minimal emissions and noise, as well as reduced life-cycle costs. The overall efficiency is characterized by the product of thermal and propulsive efficiencies $\eta_{overall} = \eta_{propulsive}\eta_{thermal})$[2]. Thermal efficiency pertains to the engine’s capacity to transform thermal power from fuel combustion into mechanical shaft power. The thermal efficiency of a jet engine is significantly influenced by the inlettemperature at the high-pressure (HP) stage turbine, the engine'shottest section. Higher inlet temperatures at the HP stage turbine enable cleaner fuel combustion, thereby enhancing engine efficiency through reduced fuel consumption and lower pollutant emissions.

Material Trends

Over the past 50 years, the temperature at the HP stage turbine has increased from 600°C to 1500°C, resulting in a 60% rise in thrust and a 20% reduction in fuel consumption [3]. The inlet temperature at the

HP turbine stage is determined by the thermal properties of the materials used. Currently, HP stage turbine components are constructed from Nickel-based superalloys, capable of operating at 1500°C with the support of advanced cooling channels and thermal barrier coatings. The complex cooling system channels relatively cool air at 650°C from the compressor through passages in the HP stage turbine. This cooling air forms a thin film around the HP turbine nozzle and blades, allowing them to function 300°C above the melting point of Nickel-based superalloys as shown in figures 2 and 3below [3].

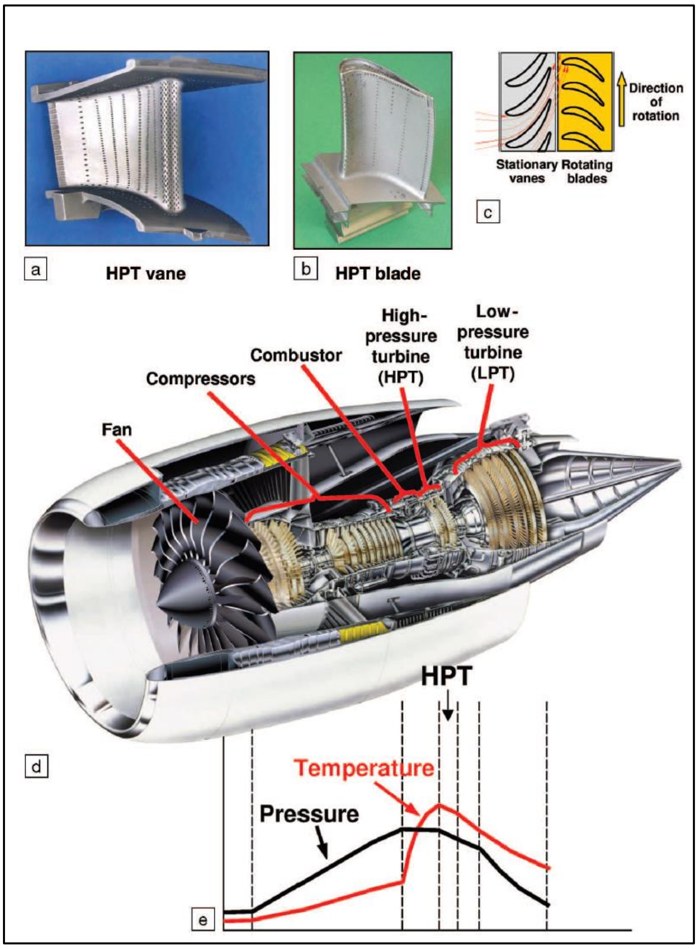

Figure 2: (a),(b) & (c) – Details of HPT nozzle & blade, (d) – Illustration of a jet engine, and (e) – Pressure and temperature trends from the front to the back of the engine [5]

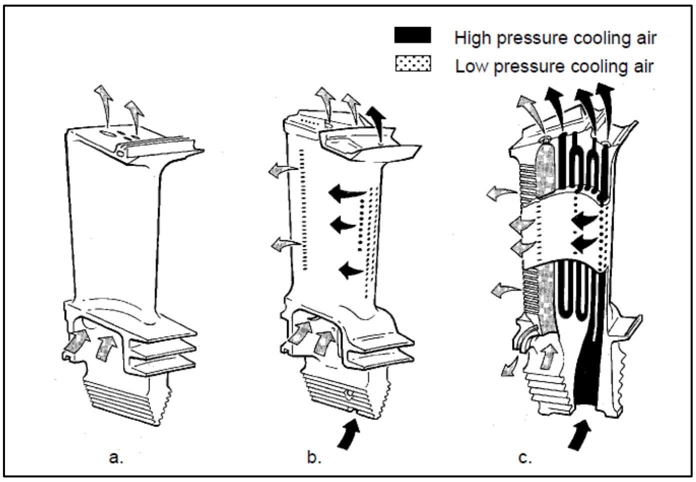

Figure 3: High-pressure turbine blades with internal cooling channels [14]

This method is highly effective and, if applied to an ice blade placed inside a conventional oven, the ice would remain frozen indefinitely [4]. However, this technology restricts the inlet temperature at the HP stage turbine and the resulting thrust, thus limiting the overall efficiency of the jet engine.

To enhance engine efficiency, new structural materials must be developed that can endure higher inlet temperatures in the HP stage turbine while simultaneously reducing the engine's structural weight.

Material Selection

There are four primary categories of materials capable of withstanding the extreme service temperatures in the high-pressure (HP) stage turbine:

(1) Refractory Metals – Refractory metals, characterized by their very high melting points (above 2000°C) and exceptional resistance to heat and wear, have been considered. However, their poor oxidation resistance at elevated temperatures and greater weight compared to current Nickel-based super-alloys make them unsuitable for jet engine applications [5].

(2) Monolithic Ceramics – Although many monolithic ceramics exhibit high strength at elevated engine operating temperatures, their inherent brittleness precludes them from being used in such applications.

(3) Intermetallic Compounds – Intermetallic compounds such as NiAl and TiAl offer appealing properties for jet engine use, including low density, high melting point, good thermal conductivity, and intrinsic oxidation resistance. Nevertheless, their low ductility at room temperature, low fracture toughness, and high manufacturing costs presents significant drawbacks.

(4) Ceramic Matrix Composites (CMCs) – CMCs are composed of two or more ceramic materials with distinct properties, which, when combined, yield a material with more favorable characteristics. CMCs consist of at least two phases: matrix and reinforcement. The matrix phase supports and encases the reinforcement phase, ensuring their relative positions are maintained, while the reinforcement phase enhances the properties of the matrix due to its unique attributes. CMCs are the most promising materials for replacing Nickel-based super-alloys in jet engines, as they exhibit excellent thermal capabilities, low density, higher hardness, improved fracture toughness, and greater resistance to brittle fracture [5].

Silicon Carbide/Silicon Carbide Ceramic Matrix Composites (SiC/SiC CMC)

Numerous types of ceramic matrix composites (CMCs) exist, each with unique properties. Among them, silicon carbide ceramic stands out as the most suitable matrix and reinforcement material for jet engine applications. SiC/SiC CMCs offer higher oxidation resistance, durability, and lower permeability compared to Carbon/SiC or Carbon/Carbon composites. Furthermore, SiC/SiC CMCs exhibit greater strength, superior thermal capabilities, lower permeability, and improved thermal conductivity and creep-rupture resistance compared to oxide/oxide CMCs [6].

Using SiC/SiC CMC components provides two primary advantages over traditional Nickel-based superalloys:

(1) The superior thermal capabilities of SiC/SiC CMCs allow for higher inlet temperatures at the HP stage turbine, reducing the need for external cooling air from the compressor.

(2) The density of SiC/SiC CMCs is 33% lower than that of Nickel-based superalloys, significantly reducing the weight of the jet engine [7]. The Mineral, Metals, and Materials Society (TMS) estimates that Nickel-based superalloys contribute to about 50% of a jet engine's weight [8].

Therefore, incorporating SiC/SiC CMC components enhances the thrust-to-weight ratio of the jet engine, leading to higher efficiency and reduced emissions of harmful exhaust gases.

(A) Mechanical Properties of SiC/SiC CMCs

When silicon carbide (SiC) fibers are embedded within a SiC matrix to create a ceramic matrix composite (CMC), the resulting mechanical properties surpass those of monolithic SiC ceramic. In SiC/SiC CMCs, the SiC matrix transfers mechanical stress to the reinforced SiC fibers, enhancing flexural resistance and fracture toughness. As a result, SiC/SiC CMCs exhibit non-brittle behavior despite being entirely ceramic. The fracture toughness of monolithic SiC is approximately 5 MPa·m^1/2, whereas that of SiC/SiC composites ranges from 20 to 30 MPa·m^1/2 [6]. Moreover, the mechanical properties of SiC/SiC CMCs can be further tailored by adjusting the architecture of the fibers (size, composition, and alignment), the interfacial layers of material, and the thickness of the composite.

(B) Thermal Properties of SiC/SiC CMCs

SiC/SiC CMCs demonstrate relatively high thermal conductivity, as well as high creep and oxidation resistance, enabling them to endure elevated service temperatures. These composites exhibit thermal conductivity that is 6.6 times greater at room temperature and 1.3 times greater at 1000°C compared to Nickel-based superalloys [6]. SiC/SiC CMCs can easily withstand temperatures exceeding 1482°C with reduced cooling air requirements compared to current Nickel-based superalloys [9]. Consequently, less compressed cooling air is diverted from the engine core, allowing engines to operate at higher thrust and achieve greater efficiency.

(C) Chemical Properties of SiC/SiC CMCs

The oxidation resistance of SiC/SiC CMCs is a crucial factor for high-temperature applications. In CMCs, the oxidation mechanism is temperature dependent. At operating temperatures of 1000°C and above, a protective oxide layer forms through passive oxidation of the SiC/SiC CMC, shielding the composite. Conversely, at temperatures of 1000°C or below, the lack of a protective oxide layer accelerates the degradation of the fiber-matrix interface. Additionally, atmospheric corrosive factors such as H2O, NOx, NaCl, and kerosene (jet fuel) derivatives like sulfides, Na2SO4, and K2SO4 expedite the corrosion process in CMCs [6]. Therefore, environmental barrier coatings are necessary to prevent excessive oxidation and corrosion, thereby enhancing the durability of SiC/SiC CMC jet engine components.

SiC/SiC CMC Manufacturing

There are three essential steps to manufacture SiC/SiC CMCs as explained below.

(A) Reinforcing fibers

The predominant commercial method for producing polycrystalline ceramic fibers involves spinning and heat-treating chemically derived precursors. Specifically, a preceramic polymer containing silicon and carbon is spun and then pyrolyzed to create a SiC ceramic fiber (refer to Appendix 4). A key characteristic of polymer derived SiC fibers is their ultra-fine microstructure with grain sizes in the nanometer range, which imparts excellent tensile strength to the fibers [10].

(B) Interface Coating

An interface coating is applied to the SiC fibers to prevent bonding with the SiC matrix and maintain fracture toughness. This coating creates a weak interface between the fibers and matrix, thereby preventing crack propagation from the matrix to the fibers. Additionally, interface coatings protect the SiC fibers from environmental degradation during the composite manufacturing process. To sustain the weak and de-bonded fiber-matrix interface, the coating must be chemically and mechanically stable at high temperatures and in corrosive environments. Boron Nitride (BN) interface coating is employed with SiC fibers, as it provides the best damage tolerance among all types of interface coatings [9].

(C) Matrix

There are several manufacturing processes for producing SiC matrices, with liquid silicon infiltration (LSI) being the fastest and most cost-effective method for large-scale production of ceramic matrix composites (CMCs). CMCs produced using LSI exhibit low porosity, minimal impurities, and enhanced corrosion resistance. The process begins with BN-coated SiC fibers impregnated with a carbon-rich resin. This impregnation creates a tape of fibers, which is then molded to the desired dimensions. The molded tape undergoes heat treatment to cure and set the component's geometry. During pyrolysis, unwanted compounds are burned off, leaving behind a porous carbon matrix around the SiC fibers. When the matrix is immersed in a furnace, the pores are filled with molten silicon, which reacts with the carbon to form the SiC matrix as shown inFigure 4 below [11].

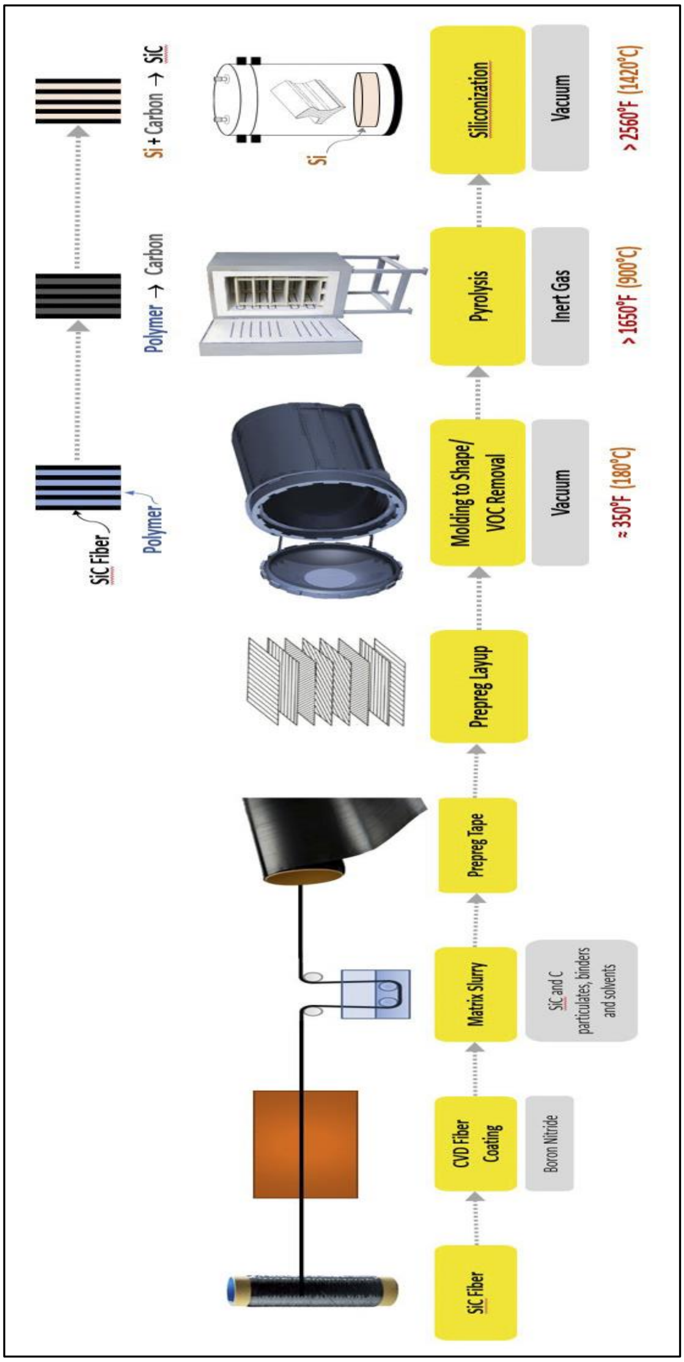

Figure 4: Process chain for SiC/SiC CMCs manufactured using LSI technique [7]

Recycling

The need for recycling ceramic matrix composites (CMCs) is not imminent due to their superior durability and low corrosion treatment and maintenance requirements. However, several challenges are associated with recycling CMCs: (1) the recycling process is expensive and yields a small quantity of recyclable material compared to metals, and (2) the presence of heterogeneous phases complicates the recycling process. Despite these challenges, techniques exist to recover energy from CMCs through combustion. These energy recovery processes are effective at producing energy, but the ultimate goal is to reclaim the material from CMCs for future use [12]. Currently, CMCs remain partly experimental, and as research and development progress to identify efficient recycling methods, the use of CMCs will become more sustainable.

Benefits

Several sustainability issues related to the manufacturing and recycling of CMCs need to be addressed to maximize environmental benefits. During the production of SiC/SiC CMCs, various gases and chemicals are emitted as by-products. However, the efficiency gains provided by these CMC components in aircraft are expected to result in a net positive environmental impact over time. Engines built with SiC/SiC CMCs could reduce carbon dioxide and nitrous oxide emissions by up to 30% compared to engines constructed from Nickel-based superalloys [13]. The emissions produced by an engine per flight are far more harmful than the waste generated during the fabrication of SiC/SiC CMC components. Within a few years, it is anticipated that aircraft equipped with SiC/SiC CMC parts will not only break-even but also surpass the initial environmental drawbacks.

Conclusion

Currently, the most advanced SiC/SiC ceramic matrix composite (CMC) engine in service is CFM's LEAP engine, featuring a turbine shroud lining made of SiC/SiC CMC. Implementing this single SiC/SiC CMC component has achieved a 15% fuel savings for the LEAP engine compared to its predecessor, the CFM 56 engine [9]. GE is currently developing the next-generation engine, GE9X, which incorporates multiple CMC components, including HP turbine shrouds, turbine nozzles, and combustor liners. Extensive testing of the GE9X has shown that it will produce 30% less nitrous oxide than the average large engine, have a 10% lower fuel burn rate than its predecessor, the GE90, and offer a 5% better fuel consumption rate compared to any extra wide-body aircraft engine [13].

While the aforementioned parts are static components of the jet engine, the primary objective is to eventually manufacture rotating components, such as turbine blades, from SiC/SiC CMC. Rotating components made from SiC/SiC CMC would be lighter, allowing for the reduction of other engine components like bearings and disks, further decreasing overall weight and enhancing engine efficiency. A materials research team in Japan has already successfully fabricated and tested SiC/SiC CMC turbine blades.

Future

Future challenges include lowering manufacturing costs, further advancing SiC/SiC CMC production technology, and developing effective recycling processes. With enhanced efficiency, reduced fuel consumption, lower emissions, and minimal maintenance requirements, CMCs are poised to revolutionize the aerospace industry. Therefore, SiC/SiC CMCs have a promising future in jet engine applications.

References

[1] D. Airways, "Evolution of Jet Engines," [Online]. Available: http://www.dj-airways.com/evolution-of-jet-engines/. [Accessed 10 October 2017].

[2] Rolls Royce Plc, The Jet Engine, Fifth Edition, Derby, 1996.

[3] M. Felice, "MATERIALS THROUGH THE AGES: MATERIALS FOR AEROPLANE ENGINES," Materials World magazine, 2013.

[4] S. Milne, "Advanced Metal Alloys and Their Applications in Jet Engines," Azo Materials , 2014.

[5] J.H.Westbrook and J.-C. Zhao, "Ultrahigh-Temperature Materials for Jet Engnies," *Materials Research Society Bulletin*, pp. 622-630, September 2003.

[6] M. Florian, L. E. d. Carvalho and C. A. A. Cairo, "SiCf/SiC Composite: Attainment Methods, Properties and Characterization," in *Advances in Ceramics - Synthesis and Characterization, Processing and Specific Applications*, Shangai, INTECH, 2011, pp. 173-190.

[7] G. Gardiner, "The next generation of ceramic matrix composites," 11 May 2017. [Online]. Available: https://www.compositesworld.com/blog/post/the-next-generation-of-ceramic-matrix-composites. [Accessed 15 October 2017].

[8] R. Bowman, "Superalloys: A primer and History," The Mineral, Metals, and Materials Society, [Online]. Available: http://www.tms.org/meetings/specialty/superalloys2000/sup eralloyshistory.html. [Accessed 17 October 2017].

[9] R. Lowden, K. More, J. Haynes, Y. Katoh, E. Lara-Curzio and R. Dinwiddle, "Ceramic matrix composites take flight in LEAP jet engine," Oak Ridge National Laboratory, 3 January 2017. [Online]. Available: https://www.ornl.gov/news/ceramic-matrix-composites-take-flight-leap-jet-engine. [Accessed 25 October 2017].

[10] J. A. DiCarlo and H.-M. Yun, "Non-oxide (Silicon Carbide) Fibers," Springer, 2005.

[11] D. Kopeliovich, "Fabrication of Ceramic Matrix Composites by Liquid Silicon Infiltration (LSI)," SubsTech Substances & Technologies, [Online]. Available: http://www.substech.com/dokuwiki/doku.php?id=fabrication_of_ceramic_matrix_composites_by_liquid_silicon_infiltration_lsi. [Accessed 29 October 2017].

[12] Yang, B. Irion, D. v. Heerden, P. Kuiper and H. d. Wit., "Recycling of composite materials," January 2012. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0255270111002029. [Accessed 30 October 2017].

[13] General Electric Aviation, "GE9X Commercial Aircraft Engine," [Online]. Available: http://www.geaviation.com/commercial/engines/ge9x-commercial-aircraft-engine. [Accessed 21 October 2017].

[14] C. Estrada, "New Technology used in Gas Turbine Blade Materials," *Scientia et Technica Año*, vol. XIII, no. 36, 2017.