Development of Graphene Reinforced Composite Materials for Turbine Blades: A Review

K N Sanjeev Kumar[1], Sanjeev Sharma[2], Dr. Abdel-Hamid I. Mourad[3], PB Sharma[4]

[1]PhD Student, ASET, Amity University, Gurgaon, India
[2]Professor, Head of Mechanical Engineering, ASET, Amity University, Gurgaon, India
[3]Professor, Mechanical Engineering Department, College of Engineering, United Arab Emirates University, UAE
[4]Vice Chancellor, Amity University, Gurgaon, India

Abstract
The study highlights recent advancements in high-performance materials for turbine blades used in gas turbines and jet engines. Key research areas focus on developing materials that can withstand high temperatures (1400°C–1600°C) while resisting oxidation and corrosion, essential for enhancing efficiency and reducing emissions. Inefficiencies arise from the use of coatings and complex cooling systems, increasing the demand for materials with higher temperature tolerance. Weight reduction is another critical area of improvement, particularly in aviation applications. This paper reviews advancements in Intermetallic alloys, Metal Matrix Composites (MMCs), and Ceramic Matrix Composites (CMCs), with a specific focus on graphene composites due to their outstanding mechanical strength at elevated temperatures, lightweight composition, and high oxidative resistance. Additionally, the study explores recent developments in graphene-reinforced composites and Mo-Si-B-based alloys as potential alternatives to Ni-based super alloys, offering promising results for sustaining higher operating temperatures and enhanced performance under high-stress conditions.

Keywords: Turbine blades, Ceramic Matrix Composites, Titanium Carbide, Graphene Composites, Nickel-based Super alloys

1. Introduction

Gas turbines play a pivotal role in power generation and as thrust providers in jet aircraft. Recent material advancements in gas turbines have led to improved thermal efficiency, allowing components to withstand higher operating temperatures with enhanced strength-to-weight ratios. These developments contribute to reductions in fuel consumption and CO_2 emissions, yielding up to a 2% increase in turbine efficiency, increased thrust for aviation, and cost savings in power generation.

Over the past few decades, there has been substantial progress in developing materials capable of withstanding high temperatures, along with innovations in thermal barrier coatings and manufacturing methods. Advanced alloys now endure average operational temperatures near 1050°C, with localized airfoil regions peaking at 1200°C, which approaches 90% of their melting thresholds [1, 2]. Currently, nickel-based super alloys, which enable turbine operation at temperatures as high as 1150°C [2], are

widely used due to their toughness, resistance to high-temperature deformation and fracture, and resilience in chemically reactive or oxygen-rich settings [1]. These super alloys constitute about 40-50% of a jet engine's mass, primarily utilized in high-temperature sections like high-pressure turbine blades, afterburners, combustion chambers, and thrust reversers [1]. While different materials are applied for different components of the gas turbine (Figure 1), Turbine blades, in particular, demand materials that can endure substantial mechanical loads from rapid rotation while operating above 1000°C [3].
A critical challenge in turbine material development is creating materials that maintain high mechanical strength over a broad temperature spectrum and can be manufactured into the complex shapes required for turbine blades. Investment casting is frequently employed to produce creep-resistant blades with intricate cooling passages and controlled grain structures, often as single crystals to eliminate high-angle grain boundaries [4, 5]. Using single-crystal structures in high-temperature zones and equiaxed grains in cooler areas helps reduce damage accumulation under thermal stress [6]. Advances in materials with strength between 1400°C and 1600°C, coupled with improved oxidation and corrosion resistance, are necessary to elevate operating temperatures and improve efficiency. Greater efficiency leads to reduced emissions and increased profitability.

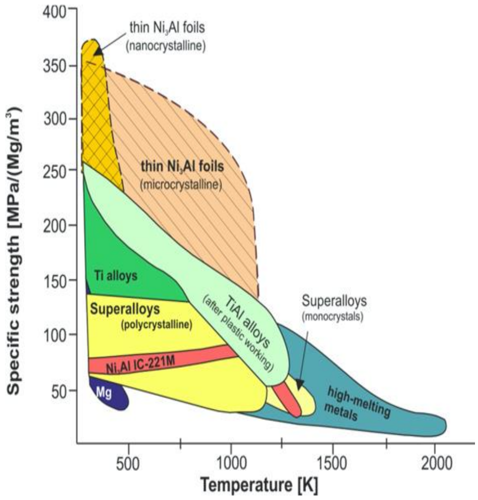

Figure 1: Temperature vs. specific strength for super alloy [3]

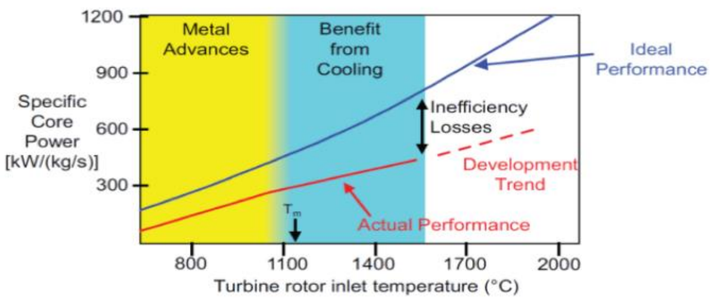

Figure 2: Specific core power vs. turbine rotor inlet temperature[7]

While coatings and cooling systems allow turbine materials to operate at temperatures as high as 1500°C, they introduce inefficiencies by consuming significant power for blade cooling, which can impact engine performance (Figure 2) [7]. Existing coating methods also offer limited oxidation protection, causing premature aging of blade substrate materials in severe service conditions [8]. Enhancing nickel-based super alloys has become challenging due to constraints posed by their melting points [9]. Therefore, there is a growing need for materials with improved high-temperature capacity, specific strength, and oxidation resistance. Modern jet engines experience turbine inlet temperatures surpassing 1649°C (3000°F), while non-aviation turbines operate near 1482°C (2700°F). Consequently, next-generation turbine blades require materials capable of sustaining these high temperatures while retaining robust mechanical properties.

2. High Performance Materials

A literature review examined recent advancements in high-performance materials for turbine blades, specifically intermetallic alloys, metal matrix composites (MMCs), ceramic matrix composites (CMCs), and graphene-based nanomaterial, as they align with the unique demands of turbine blade applications. These materials are evaluated for their high-temperature performance, corrosion resistance, structural durability, and strength-to-weight ratio, all essential for enduring the extreme conditions faced by turbine blades.

2.1 Inter-Metallic Alloys

Over the past 30 years, significant progress has been made in developing intermetallic alloys, particularly γ-TiAl, NiAl, and platinum-group metal (PGM) compounds. Titanium-based alloys, such as Ti3Al, show potential but are constrained by performance and manufacturing challenges, limiting their use to temperatures around 600°C [10]. γ-TiAl alloys, like Ti-48Al-2W-0.08B, demonstrate excellent creep and oxidation resistance up to 750°C, with a 50% increase in elastic stiffness over conventional materials [11–14]. Advances in processing, including recrystallization and surface fluorination, have extended the high-temperature resilience of γ-TiAl to approximately 1050°C [15]. Despite these improvements, further optimization is needed to enhance γ-TiAl's oxidation resistance in extreme conditions [16]. With their favorable strength-to-weight ratio and high-temperature creep resistance, γ-TiAl alloys hold promise for lower-pressure turbine sections but still require advancements to fully meet the demands of high-temperature applications. NiAl alloys, particularly when alloyed with Ni2AlTi, provide significant creep strength at around 1100°C but depend on refractory elements (e.g., Mo, Cr) to achieve balanced toughness and strength, with ductility and toughness at ambient temperatures remaining a challenge [17, 18].
PGMs, while excelling in oxidation resistance with minimal alloying, are restricted by high density and cost, which limit their practical applications in turbine environments [19]. While γ-TiAl, NiAl, and PGM alloys each offer unique properties suited for turbine applications, yet ongoing material innovations are needed to address their individual limitations.

2.2 In-Situ Composites

Ni-based single crystal super alloys are limited to operating temperatures below 1200°C, making them unsuitable for turbine blades in high-temperature gas turbine (GT) applications. SiC/SiC composites, composed of silicon carbide fibers within a silicon carbide matrix, have shown resilience at temperatures 93°–149°C higher than nickel super alloys, thereby reducing the need for complex cooling systems and enhancing jet engine efficiency. These composites are currently used in LEAP and GE9X engines, and their application has been successfully demonstrated in low-pressure turbine blades for the F414 engine [20, 21]. However, SiC/SiC composites remain susceptible to combustion environments, limiting their broader application. To address this, eutectic-oxide CMCs are under development, though challenges remain in manufacturing complex geometries, such as turbine blades, with CMCs.
Mo-based alloys are promising for ultra-high-temperature applications due to their high melting point (2623°C) compared to Ni. The Mo-Si-B alloy system, however, is vulnerable to oxidation at elevated

temperatures and requires stable reinforcements to enhance oxidation resistance. The MoSiBTiC alloy (65Mo-5Si-10B-10Ti-10C (at%)) has shown excellent creep resistance in the 1400–1600°C range [22], achieving a creep rupture time of 1000 hours at 137 MPa between 1350–1400°C, outperforming SiC/SiC composites in similar conditions[23]. Recent research found that adding Cr and Al to a Ti5Si3-incorporated MoSiBTiC alloy significantly improved its oxidation resistance at 800°C by forming $Cr_2(MoO_4)_3$ and $Al_2(MoO_4)_3$ in the oxide layers.

While SiC/SiC composites and Mo-based alloys demonstrate high-temperature stability, further advancements in oxidation resistance and manufacturability are essential for turbine blade applications operating at 1400°C–1600°C.

2.3 Graphene Composites

Graphene, a single layer of carbon atoms arranged in a two-dimensional hexagonal lattice, exhibits exceptional mechanical properties, including a tensile strength of approximately 130 GPa—about 200 times that of steel. Its high thermal conductivity and electrical properties make it an excellent reinforcement material for intermetallic, metal matrix composites (MMCs), and ceramic matrix composites (CMCs) [24].

Graphene-Reinforced Aluminum Composites: Incorporating graphene into aluminium matrices has led to significant enhancements in mechanical properties. Graphene/alumina hybrid-reinforced aluminum composites demonstrate superior ultimate tensile strength, yield strength, and elastic modulus compared to pure aluminum [25]. However, these composites exhibit reduced ductility, indicating a trade-off between strength and flexibility. Additionally, graphene nano flakes (GNFs) have been used to reinforce aluminium alloys via powder metallurgy, resulting in notable increases in mechanical properties while maintaining the characteristic ductility of aluminium and minimizing interfacial reactions [25]. Enhanced thermal conductivity and improved heat dissipation due to graphene reinforcement are especially advantageous for high-temperature applications, as these properties contribute to the longevity and operational stability of turbine components under thermal stress [26].

Graphene-Reinforced Nickel-Based Alloys: Graphene-reinforced nickel-based alloys demonstrate strong potential for high-temperature turbine applications, offering enhanced mechanical strength, toughness, and thermal stability. Research on Ni-Ti-Al/Ni_3C composites with graphene shows a 73% increase in strength, a 6% improvement in Young's modulus, and a 44% boost in toughness at temperatures up to 1000°C, with minimal loss in ductility (28%) [27]. Graphene's reinforcement enhances load-bearing capacity and damage tolerance, enabling these alloys to endure high cyclic stresses typical in turbine operations, thereby extending component lifespan and boosting engine efficiency. Recent studies further indicate that Graphene oxide in nickel super alloys enhances both oxidation resistance and durability, making these alloys highly suitable for prolonged high-stress applications in gas turbines, where efficiency and resilience are critical under extreme conditions [28, 29, 30].

Graphene-Reinforced Titanium Alloys: Research into Graphene-reinforced titanium alloys demonstrate strong potential for high-temperature turbine applications, offering enhanced mechanical properties, reduced weight, and potential improvements in oxidation resistance. Titanium/graphene nanoplatelet (GNP) composites, produced via cold pressing and sintering, exhibit substantial gains in hardness (613 HV) and shear strength (728 MPa), making them suitable for turbine environments with intense rotational stresses and high loads [31]. These alloys provide a significant improvement over traditional intermetallic and in-situ composites in strength, weight reduction, and high-temperature performance. The carbon fiber/graphene-coated reinforced TiAl alloy composite (CFGRTAC) achieved a tensile strength of 2312

MPa and an elongation at break of 26.27%, with a 20.1% reduction in density compared to Ti-45Al-8Nb alloys [32]. This reduction in weight is advantageous for aerospace turbines, where lightweight materials improve fuel efficiency and thrust without compromising structural integrity. Recent advances also show that graphene-infused composites offer increased thermal fatigue resistance, allowing turbine blades to withstand high-cycle demands and extend operational life in gas turbine engines [33]. While ongoing research focuses on optimizing oxidation resistance, Graphene's high thermal conductivity and potential for surface modifications offer pathways to enhance the durability of titanium alloys in oxidative, high-temperature environments.

Graphene-reinforced composites offer significant potential for high-temperature applications, providing substantial improvements in mechanical properties and thermal stability over traditional intermetallic alloys and in-situ composites. However, challenges remain in optimizing the dispersion of graphene within metal matrices and enhancing oxidation resistance at elevated temperatures. Innovations in processing techniques, such as spark plasma sintering and chemical vapor deposition, have improved the dispersion of graphene within metal matrices, leading to composites with superior mechanical properties and thermal stability. Furthermore, surface modifications of graphene, including functionalization with oxidation-resistant elements, have been explored to enhance the oxidation resistance of these composites at elevated temperatures. Recent research highlights that graphene-reinforced CMCs show enhanced thermo-mechanical stability, positioning them as promising candidates for turbine blade applications, where both high thermal conductivity and resistance to oxidation are crucial [34]. Ongoing research is essential to address these challenges and fully realize the potential of graphene-reinforced composites in high-performance turbine blade applications.

3. Results and Discussion

Recent advancements in high-performance materials for turbine blades underscore the potential of emerging composites and alloys to withstand the extreme conditions found in gas turbines and jet engines. Key findings across material types are summarized below, highlighting specific strengths and areas for further improvement.

High-Temperature capabilities and creep resistance of CMCs: Ceramic matrix composites (CMCs), particularly fiber-reinforced CMCs like C/SiC and SiC/SiC, are promising for applications at temperatures above 1400°C due to their high-temperature resilience, mechanical strength, and corrosion resistance. These composites are already utilized in aerospace, yet their creep resistance and thermal stability require enhancement to meet the rigorous demands of turbine blades under cyclic thermal stresses [35, 36]. Further integration of graphene in CMCs has been shown to improve their thermo-mechanical stability, positioning these composites as candidates for turbine applications that require high-temperature durability and resistance to oxidation [34].

Graphene Composites for enhanced mechanical properties: Graphene-reinforced composites, such as graphene/alumina hybrid and graphene-reinforced aluminium, have shown substantial increases in tensile strength and modulus, though there is a trade-off with ductility [25]. This enhancement of mechanical properties positions graphene composites as candidates for high-stress turbine applications, where lightweight strength and structural integrity are crucial. Moreover, graphene's high thermal conductivity supports efficient heat dissipation, which is advantageous for high-temperature operations that challenge conventional aluminum composites [26].

Graphene-reinforced Nickel-based alloys for higher load-bearing capacity and damage tolerance: Nickel-based alloys reinforced with graphene show impressive gains in strength, toughness, and thermal stability. For example, Ni-Ti-Al/Ni_3C composites with graphene reinforcement achieve a 73% strength increase and a 44% improvement in toughness at temperatures up to 1000°C [27]. These advancements make graphene-reinforced nickel alloys well-suited for high-performance turbine blades, where load-bearing capacity and damage tolerance are essential. Recent studies further highlight that graphene oxide in nickel superalloys improves oxidation resistance, enabling these alloys to endure prolonged high-stress conditions and making them particularly valuable for gas turbine blades [28, 29, 30].

Graphene-reinforced Titanium alloys for weight reduction and durability: Graphene-reinforced titanium alloys, such as titanium/graphene nanoplatelet (GNP) composites, offer enhancements in hardness and shear strength, along with a 20% density reduction compared to standard titanium alloys [31, 32]. The carbon fiber/graphene-coated TiAl alloy (CFGRTAC) achieves significant tensile strength and elongation, making it advantageous for aerospace turbine blades, where weight efficiency translates into fuel savings and performance benefits. Graphene's high thermal conductivity also suggests potential for improved oxidation resistance, further supporting high-temperature applications. Additionally, graphene-reinforced titanium alloys demonstrate enhanced thermal fatigue resistance, enabling these materials to withstand high-cycle operational demands, which is critical for jet engine applications where thermal cycling is frequent [33].

Mo-Si-B-based alloys and Graphene's role in oxidation resistance: The MoSiBTiC alloy shows promise for ultra-high-temperature applications, with creep resistance up to 1600°C, outperforming SiC/SiC composites in similar conditions [22, 23]. However, improvements in oxidation resistance are necessary for sustained high-temperature performance. Adding elements like Cr and Al to these alloys forms protective oxide scales, and graphene reinforcement offers potential to enhance oxidation resistance further, given its high thermal conductivity and surface modification capabilities. Research indicates that graphene's addition can also improve the oxidation resistance of MoSiBTiC alloys by forming stable oxide layers, making these alloys more resilient under oxidative environments typical in gas turbines [34].

4. Conclusion

The study identifies the critical role of graphene and advanced composites in developing high-performance materials for turbine blades. Ceramic matrix composites, graphene-reinforced nickel and titanium alloys, and MoSiBTiC alloys each contribute unique strengths for high-temperature applications. Graphene reinforcement specifically enhances mechanical properties, thermal stability, and weight efficiency, making it integral to next-generation turbine materials. However, continued optimization in oxidation resistance and thermal durability is essential to meet the extreme demands of gas turbines and jet engines.

Novel research areas:

Building on the results and discussions, potential research areas include:

1. **Hybrid composites with Graphene and CMC/CMC-enhanced Metal Matrices**: Investigate the hybridization of graphene with CMCs or CMC-reinforced metal matrices, such as Ti/SiC or Al/SiC, to enhance oxidation resistance and mechanical performance at ultra-high temperatures. The combination of Graphene's strength and thermal conductivity with the stability of CMCs could produce composites that excel in thermal cycling and oxidative environments.
2. **Graphene-modified MoSiBTiC alloys for oxidation and creep resistance**: Further explore the hybridization of graphene with MoSiBTiC alloys. Using graphene as a reinforcing phase could offer

an innovative solution for MoSiBTiC's oxidation challenges, potentially achieving high thermal resistance through surface-functionalized graphene layers.
3. **Functionalized Graphene in fiber CMC and C/C composites**: Conduct studies on the application of functionalized graphene in fiber-reinforced CMCs and C/C composites, specifically to increase fracture toughness and thermal stability at elevated temperatures. By leveraging functionalized Graphene's affinity for certain oxide-forming elements, these composites could also achieve enhanced oxidation resistance.
4. **Graphene-enhanced coatings for existing high-temperature alloys**: Explore the application of graphene-enhanced coatings on Ni-based super alloys and Mo-based alloys. A graphene-based coating may extend the operational lifespan of existing high-temperature materials, providing an immediate enhancement to oxidation and corrosion resistance while new materials are being developed.
5. **Exploring manufacturing techniques for improved Graphene dispersion**: Investigate advanced manufacturing methods such as spark plasma sintering, chemical vapor deposition, and 3D printing for achieving uniform graphene dispersion in metal and ceramic matrices. Consistent graphene distribution could unlock higher material performance and reliability across turbine applications.

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