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THERMAL AND STRUCTURAL ANALYSIS OF T6, HAYNES 188 AND X-40 GAS TURBINE BLADE AT VARIOUS OPERATING TEMPERATURES

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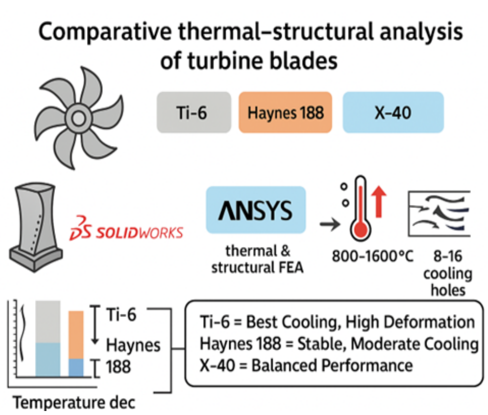
Graphical abstract



Abstract

Gas turbine blades operate under extreme thermal and mechanical loads, requiring efficient cooling strategies and materials with high-temperature resistance. This study presents a comparative thermal and structural analysis of blades made from Ti-T6, Haynes 188, and X-40 using finite element analysis (FEA). Blade models with 8, 12, and 16 radial cooling holes were developed in SolidWorks and analysed in ANSYS 2023 R1 under steady-state conditions from 800 °C to 1600 °C. Thermal performance was evaluated through temperature distribution, while structural behavior was assessed using deformation, strain, and stress. Results showed that additional cooling holes reduced blade temperature, with Ti-T6providing the best thermal performance but exhibiting higher deformation and strain due to its lower stiffness. Haynes 188 and X-40 demonstrated greater structural stability, with X-40 maintaining the most uniform stress distribution. Overall, X-40 offers the best balance between cooling efficiency and structural integrity, making it a promising choice for advanced turbine blade applications.

Keywords: Gas Turbine Blades, Finite Element Analysis, Ti-T6, Haynes 188, X-40, Cooling Holes, ANSYS.

1.0 INTRODUCTION

Gas turbines are advanced mechanical devices that convert the energy stored in fuel into mechanical power through a continuous combustion process. Widely used in power generation, aviation, and marine applications, gas turbines operate on the Brayton cycle and consist primarily of a compressor, combustion chamber, and turbine section. A critical component of the turbine section is the blade, which extracts energy from high-temperature, high-pressure gases and converts it into rotational motion [1, 2]. These blades must withstand extreme mechanical and thermal stresses, requiring them to be made from highly specialized materials. Typically, superalloys based on nickel or cobalt are used due to their excellent high-temperature strength, corrosion resistance and durability. To further enhance performance, blades are often coated with thermal barrier coatings and are internally cooled using complex cooling passages. The manufacturing of turbine blades is a highly precise process involving advanced techniques such as investment casting, directional solidification, and in some cases, additive manufacturing. These processes ensure the blades meet the stringent requirements for performance and longevity in harsh operating environments. The combination of advanced materials and sophisticated manufacturing processes plays a crucial role in improving the efficiency, reliability, and durability of modern gas turbines [3]. In this research, finite element analysis (FEA) based simulation of gas turbine blades are conducted to study the thermal and structural properties on three different materials, viz, Ti-T6, Haynes 188 and X-40 in various conFigureurations of 8, 12 and 16 holes by varying the temperature in the range of 800° C to 1600° C.

2.0 LITERATURE REVIEW

Many researchers have conducted elaborate simulation in identifying the right material and turbine blade design for optimum results. Raga et.al [3] studied a gas turbine designed to convert the heat energy of fuel into useful work. Turbine blades are most important components in a gas turbine power plant and is used to transfer the energy from the gases to the turbine rotor. The turbine blades are mainly affected due to static loads and the temperature has significant effect on the blades. Deepanraj et.al [4] considered titanium – aluminium alloy as the blade material and performed structural and thermal analysis by varying the number of cooling passages. They also studied the effect of varying the cooling air temperature on the temperature distribution in the blades. It is concluded that the blade conFigureuration with 8 holes provided an optimum blade temperature. Many researchers have conducted simulation analysis on turbine blades made of Inconel 718 and compared its performance with that of other materials [5]. Bhatti et al. [6] performed transient state stress analysis on an axial flow gas turbine blade and disk using finite element technique. They chose Inconel 718, a high heat-resistant alloy of chromium, nickel and niobium, to analyse the centrifugal and thermal stresses arising in the disk. Matta et al [7] analysed the stress developed in N – 155 and Inconel 718 blade materials. On solid blades, it is reported that Inconel 718 is better suited for high temperature operation. This research suggested a cooling technology which has three main parts: a) the leading edge provided with impingement cooling; b) the middle section of blade containing cooling pipes with obstacles provided along the length to enhance turbulence in the cooling air and c) the trailing edge of the blade with pin – fins for effective cooling. Lava et al., [8] examined the heat transfer in gas turbines in four different conFigureurations consisting of blades with and without holes. The research concluded that the blade with 13 holes is considered as optimum. Steady state thermal and structural analysis were also conducted using ANSYS software on Chromium Steel and Inconel 718 turbine blades. While comparing these materials, Inconel 718 is better in thermal properties and the induced stresses are lesser in Inconel 718, compared to Chromium steel. Very few literatures pertaining to gas turbine blades made of Ti-T6, Haynes 188 and X-40 are available. The temperature distribution in turbine blades were also analysed by researchers [9-13]. Adel et al [14] analysed air cooled blades using Computational Fluid Dynamic (CFD). The research concluded that based on the boundary conditions, the blade metal temperature was relatively cooler than the temperature of the surrounding gases. The results also indicate a temperature difference of upto 450 °C between the leading and trailing edges. Further, the creep and fatigue properties of turbine blade materials were studied by many researchers [15, 16]. John et.al [17] modeled the gas turbine blades using CATIA software and performed static and dynamic stress analysis using ANSYS software. Campbell’s diagram, also called as Interference diagram, is used to study the natural frequencies and mode shape of the turbine blades. Gurrappa et al., [17] analyzed the importance of thermal barrier coating for turbine blades made of super alloys. The thickness of the coating required was also analyzed. Researchers also attempted to optimize the turbine cooling parameters [18-20]. Genetic algorithm-based optimization of a laterally diffused hole for enhancing the film cooling effectiveness under various rotational speeds were studied by Moeini et al., [21].

Although several studies [5-21] have investigated the thermal and structural behavior of gas turbine blades, most prior research has concentrated on conventional alloys such as Inconel 718 or chromium-based steels, often with a focus on either thermal or structural performance in isolation. However, limited attention has been given to the comparative evaluation of Ti-T6, Haynes 188, and X-40 alloys under identical operating conditions. In particular, the combined effect of extreme temperature ranges (800°C–1600°C) and varying cooling hole conFigureurations (8, 12, and 16 holes) on both thermal management and structural stability has not been systematically addressed in earlier literature.

This study seeks to bridge that gap by conducting a comprehensive finite element analysis (FEA) that simultaneously evaluates temperature distribution, total deformation, equivalent strain, and stress responses for the three alloys. The novelty of this work lies in its dual focus on thermal dissipation efficiency and mechanical stability, providing insights into the trade-off between effective cooling and structural reliability. The key contributions include: (i) developing detailed CAD and FEA models of turbine blades with multiple cooling hole conFigureurations; (ii) generating comparative datasets across three advanced alloys at five operating temperatures; (iii) establishing that Ti-T6offers superior heat dissipation while Haynes 188 and X-40 demonstrate greater mechanical stability; and (iv) identifying X-40 as the most balanced material choice for advanced gas turbine blade applications. These findings provide valuable design guidelines for optimizing material selection and cooling strategies in next-generation turbine technologies.

3.0 METHODOLOGY

The methodology for this study involves a structured approach to analyzing the thermal and structural performance of gas turbine blades using FEA (Figure 1). The process begins with the selection of suitable materials, namely Ti-T6, Haynes 188, and X-40, known for their high-temperature resistance and mechanical strength. Subsequently, various blade models. are developed, including blades with different cooling holes (8, 12, and 16 holes) to assess the effect of cooling passages on thermal performance. The complete dimension of the turbine blade is provided in Table 1. The properties of Ti-T6, Haynes 188, and X-40 used as blade materials for analysis is shown in Table 2. The models are then subjected to different operating temperatures ranging from 800°C to 1600°C to simulate real working conditions.

Steady-state thermal and structural analyses of gas turbine blades were carried out under realistic boundary conditions to ensure accurate representation of high-temperature operating environments. The external blade surfaces were subjected to hot gas temperatures in the range of 800°C to 1600°C, with a gas-side convective heat transfer coefficient of approximately 200 W/m²·K and surface radiation modelled with an emissivity of 0.8. Internal radial cooling passages were modelled with a coolant temperature of 427°C and an average heat transfer coefficient of 5000 W/m²·K to simulate compressor bleed air. The blade root was constrained with fixed support to prevent rigid-body motion, while centrifugal body forces corresponding to a rotational speed of 10,000 rpm and an aerodynamic pressure differential of 0.25 MPa on the pressure side were applied to replicate service conditions.

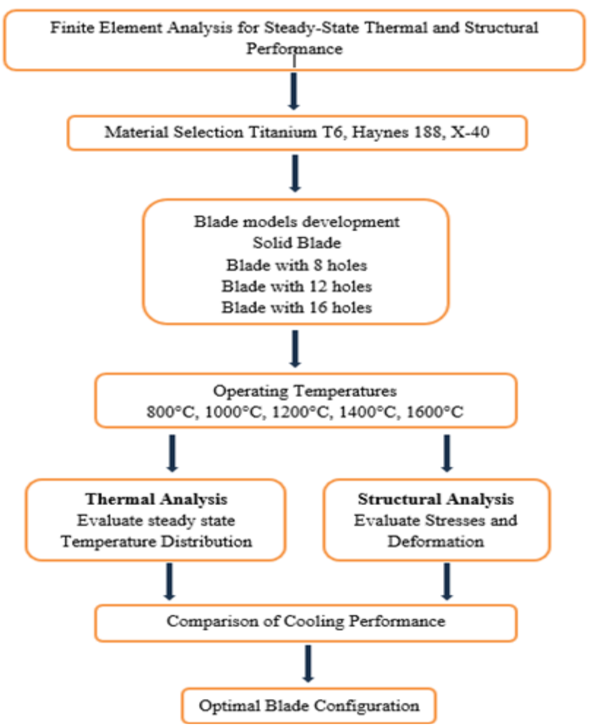


Figure 1 Methodology

Meshing was performed using quadratic tetrahedral elements, with local refinements along leading/trailing edges, fillet regions, and cooling hole interiors. Mesh quality metrics such as skewness (<0.9) and aspect ratio (<10) were maintained within recommended limits. A three-level mesh independence study was conducted with coarse (~0.55 M elements), medium (~1.1 M elements), and fine (~2.2 M elements) grids, and the medium mesh was adopted since deviations in peak temperature, von Mises stress, and tip displacement were below 2% compared to the fine mesh. Solver convergence was ensured by setting thermal residuals to 10^{-6} and force residuals to 10^{-4}, with energy imbalance <0.5% across all simulations. Validation of the thermal and structural fields was performed through comparison with trends reported in earlier literature, confirming expected gradients in temperature (hot leading edge, cooler mid-chord, and reheating near the trailing edge) and stress concentration around cooling hole ligaments and root fillets.

Sensitivity studies revealed that a ±50% variation in hot-gas heat transfer coefficient altered peak blade temperatures by less than 6%, while ±10% changes in rotational speed shifted von Mises stresses by about 10%, confirming the robustness of the simulation framework. While time-dependent damage mechanisms such as creep and fatigue, as well as coating effects, were not explicitly modelled, the comparative evaluation across Ti-T6, Haynes 188, and X-40 remains unaffected, ensuring reliable guidance for material and design selection.

Table 1 Details of Turbine Blade

Parameter	Value	Unit
Blade height, *h*	0.081833	m
Chord width, *c*	0.02727	m
Pitch, *s*	0.02264	m
Number of blades	69	-
Blade inlet angle, β_2	18.3°	deg
Blade outlet angle, β_3	54.56°	deg
Mean radius, r_m	0.2475	M

Table 2 Mechanical Properties of Ti-T6, **Haynes 188**, And **X-40** Alloys

Property	Ti-T6 (Ti-6Al-4V)	Haynes 188	X-40
Density	4.43 g/cm³	9.14 g/cm³	8.3 g/cm³
Melting Point	1660°C	1330°C	1260°C
Yield Strength	830 MPa	410 MPa	600 MPa
Ultimate Tensile Strength	900 MPa	960 MPa	750 MPa
Elongation	14-16%	51%	20%
Young's Modulus	110 GPa	220 GPa	220 GPa
Thermal Conductivity	7.2 W/m·K	10.1 W/m·K	12 W/m·K
Coefficient of Thermal Expansion	8.6 x 10^{-6} /°C	12.9 x 10^{-6} /°C	12.8 x 10^{-6} /°C

4.0 MODELLING AND ANALYSIS OF THE TURBINE BLADES

Computer-Aided Drafting (CAD) is widely used for creating 2D and 3D models. SolidWorks, a leading 3D CAD software, operates on a parametric feature-based approach for creating models and assemblies. SolidWorks also includes productivity tools like Toolbox, Utilities, and Feature Works to enhance efficiency and facilitate design modifications. In this research, turbine blades are modeled using SolidWorks 2021 software as shown in Figure 2.

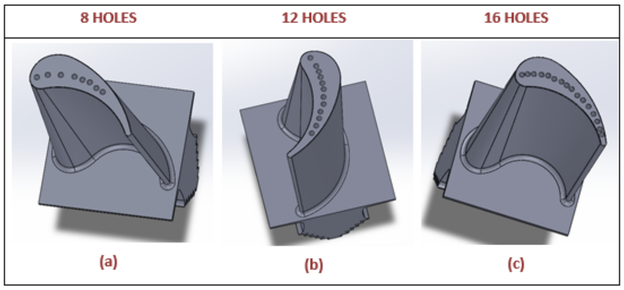
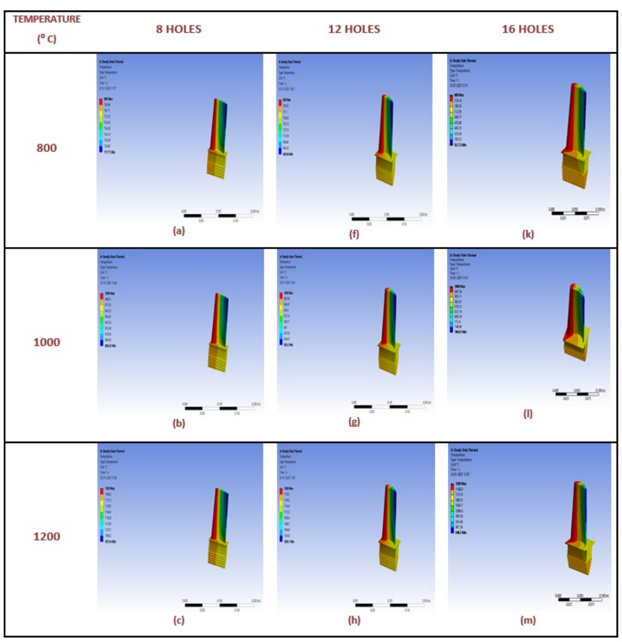


Figure 2 (a-c) Modelling of Gas Turbine Blades using SolidWorks

4.1. Thermal Analysis

The SolidWorks model of the gas turbine blades is imported to ANSYS software for performing the thermal analysis. The analysis is separately conducted for TitaniumT6, Haynes 188 and X-40 for three configurations, viz, blades with 8, 12 and 16 holes. In addition, the analysis is performed at 800 ^{o}C, 1000 ^{o}C, 1200 ^{o}C, 1400 ^{o}C and 1600 ^{o}C. Figure 3(a-o) represents the thermal analysis of Titanium Ti-6Al-4V (Ti-6). It is evident that the alloy begins to degrade at 800°C due to oxidation, strength loss, and phase transformation. The presence of 8 to 16 holes significantly increasing stress concentration and deformation risks. At 1000°C, severe oxidation and strength reduction compromise structural integrity, making the material unstable. By 1200°C, rapid degradation and phase instability render Ti-6 unsuitable for continued use. At 1400°C and 1600°C, near-complete strength loss, oxidation, and phase breakdown occur, with the holes further accelerating structural failure, leading to potential melting and catastrophic failure [22].



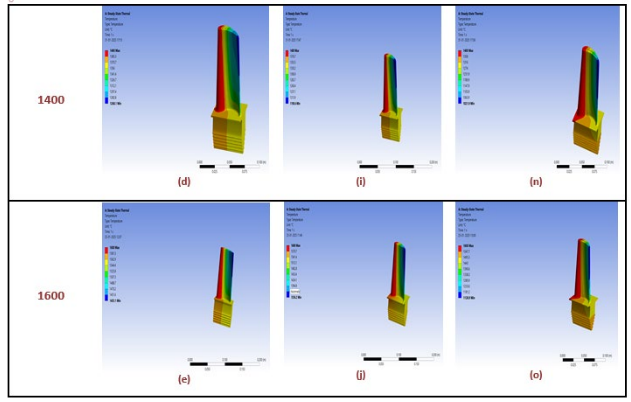


Figure 3 (a-o) Thermal Analysis of Ti-T6

To ensure reliability in high-temperature applications, the use of high-temperature coatings and alternative materials are strongly recommended. Haynes 188 is a cobalt-based superalloy known for its excellent strength and oxidation resistance at high temperatures. However, thermal analysis is essential across all temperatures to assess the performance of Haynes 188 for ensuring reliable operation in extreme high-temperature applications. Figure 4 (a-o) depicts the thermal analysis of Haynes 188 for temperatures ranging from 800 ^{o} C to 1600^{o} C. The analysis is performed for 8, 12 and 16 holes. However, the presence of more than 12 holes introduces stress concentration, thermal expansion, and creep risks, especially under cyclic loads. As temperature increases beyond 1000°C, these risks become more significant [23].

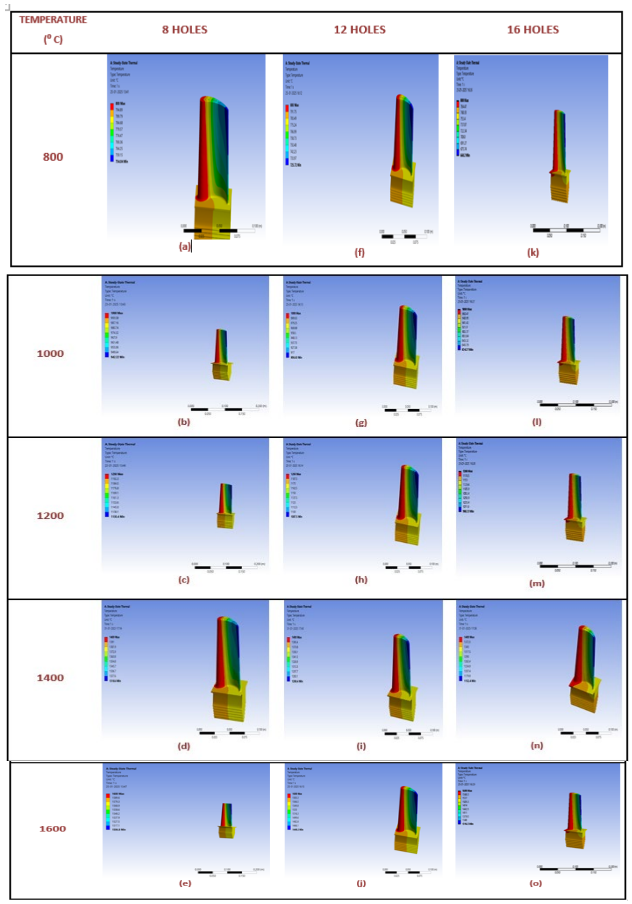


Figure 4 (a-o) Thermal Analysis of Haynes 188

At 1200°C, oxidation, creep, and strength loss accelerate, leading to reduced reliability and structural instability. Above 1400°C, rapid degradation occurs, and by 1600°C, Haynes 188 becomes unsuitable for prolonged use. X-40, a cobalt-based superalloy, maintains good oxidation resistance and mechanical strength up to 1000°C. The thermal analysis of X-40 is depicted in Figure 5 (a-o) for temperatures ranging from 800°C to 1600°C and 8-to-12-hole conditions.

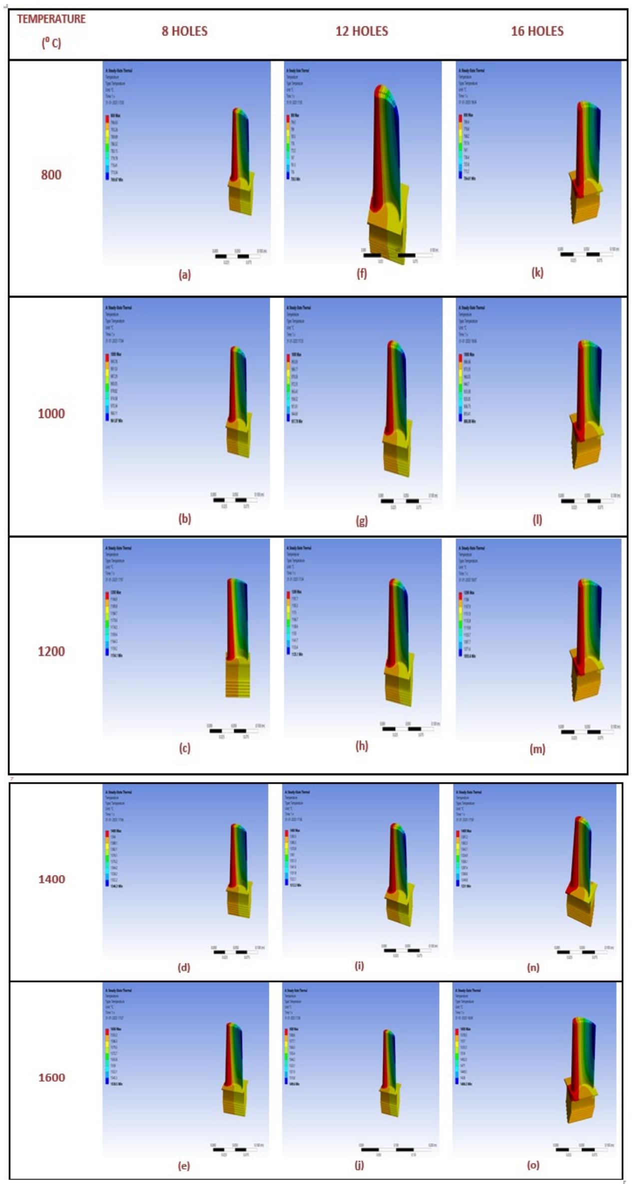


Figure 5 (a-o) Thermal Analysis of X-40

The presence of 8 to 16 holes increases stress concentration and thermal expansion, potentially reducing fatigue life and durability. At 1200°C, creep and thermal fatigue become critical concerns, with the holes further exacerbating structural degradation. As temperatures rise to 1400°C and 1600°C, accelerated oxidation, severe creep, and strength loss occur, with the holes significantly amplifying these effects, leading to a heightened risk of structural failure. Therefore, for high-temperature applications, careful design consideration and the use of alternative materials are recommended to ensure reliability.

4.2. Structural Analysis

The structural analysis of Titanium Ti-6Al-4V gas turbine blades with 8, 12, and 16 holes under high-temperature and mechanical loads focuses on total deformation, equivalent strain, and equivalent stress (Ref. Figure 6 (a-i)). As hole count increases, localized deformation, stress concentration, and strain intensify especially near hole edges and constraint points. Due to stress concentration, Ti-T6shows a consistent increase in deformation and equivalent strain as the number of holes increases.

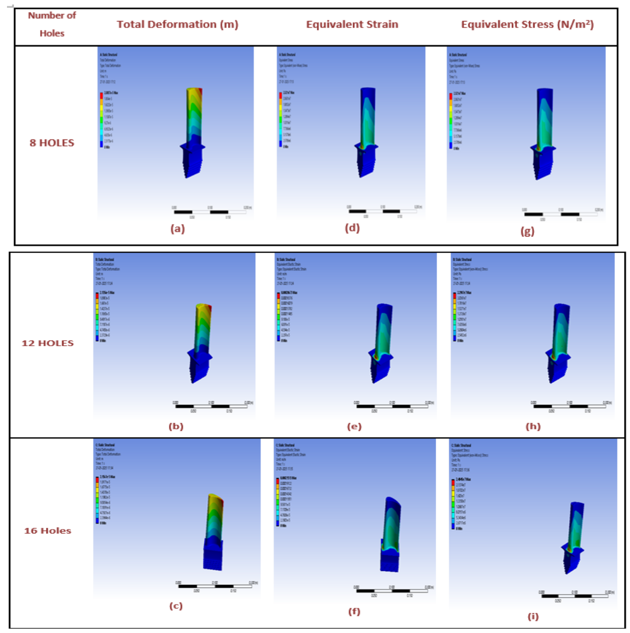


Figure 6 (a-i) Structural Analysis of Ti-T6

Moreover, the equivalent stress initially decreases followed by an increment due to increase in the number of holes. Figure 7 (a-i) depicts the structural analysis of Haynes 188 gas turbine blades with 8, 12, and 16 holes under high-temperature and mechanical loads focuses on key parameters such as total deformation, equivalent strain, and equivalent stress. As the number of holes increases, localized deformation and stress concentrations become more significant, particularly near hole edges and support points [23]. Pressure from combustion gases and aerodynamic forces leads to critical stress zones, while equivalent strain and Von Mises stress highlight areas prone to creep and fatigue. Haynes 188 exhibits relatively less deformation and equivalent strain when compared to Ti-T6. However, the equivalent stress pattern is similar to T6 [24].

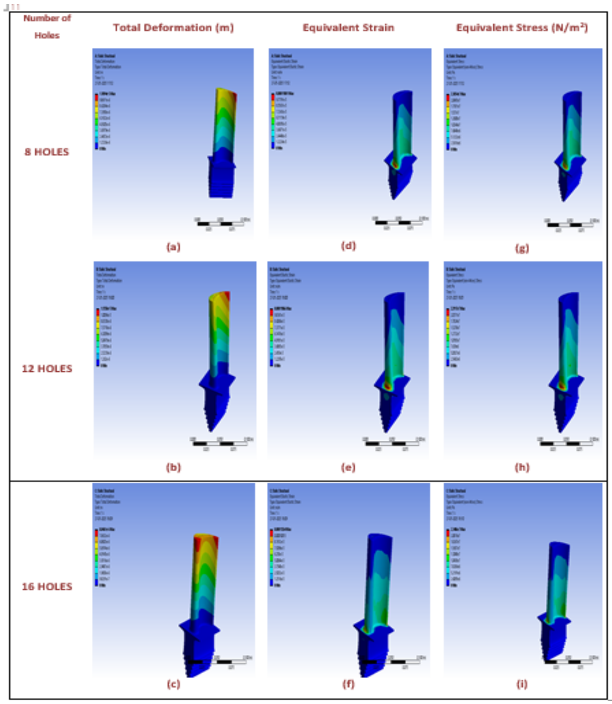


Figure 7 (a-i) Structural Analysis of Haynes 188

The structural analysis of X-40 gas turbine blades with 8, 12, and 16 holes is depicted in Figure 8 (a-i). The structural analysis of X-40 gas turbine blades with 8, 12, and 16 holes under high-temperature and mechanical loads focuses on total deformation, fixed support effects, pressure response, equivalent strain, and equivalent stress. It is evident that X-40 has better load redistribution at higher levels of perforation, and the equivalent strain also rises moderately with the increase in the number of holes[25]. Moreover, the equivalent stress variation is also minor in the case of X-40 with the increase in the number of perforations.

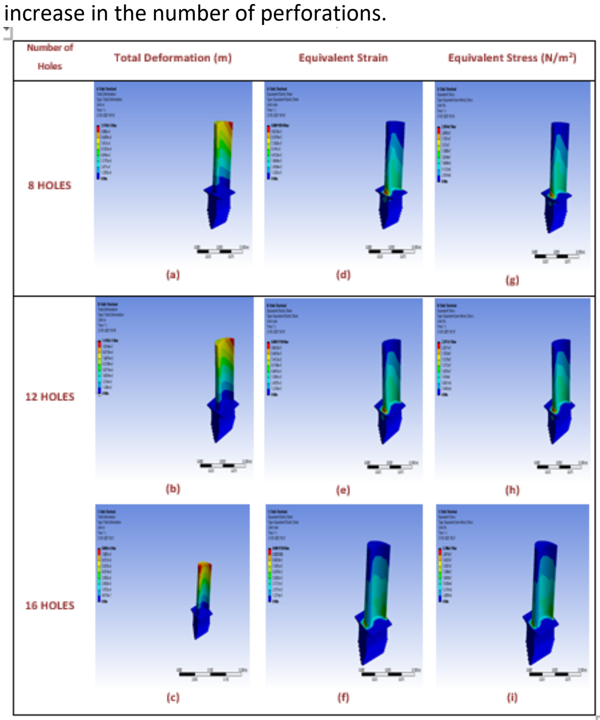


Figure 8 (a-i) Structural Analysis of X-40

5.0 RESULTS AND DISCUSSION

The temperature distribution for various conFigureurations of the turbine blades is shown in Table 3. Three materials—Ti-T6, Haynes 188, and X-40—were analyzed with 8, 12, and 16 cooling holes. The study found that increasing the number of cooling holes significantly reduced blade temperature, confirming the effectiveness of enhanced cooling mechanisms. At 800°C, Ti-T6demonstrated the best cooling performance, while X-40 retained the highest temperature, making it the least effective. These results emphasize the importance of selecting the right material and optimizing the cooling hole design to improve thermal performance and extend the lifespan of gas turbine blades. The thermal analysis of a gas turbine blade at 1000°C assessed the impact of material selection and cooling hole conFigureuration on temperature distribution. The results confirmed that increasing the number of cooling holes effectively reduces blade temperature, enhancing cooling efficiency. Among the materials, Ti-T6demonstrated the best heat dissipation, maintaining the lowest temperatures, while Haynes 188 and X-40 retained more heat. The thermal analysis at 1200°C shows that Ti-T6 consistently has the lowest temperatures, indicating superior heat dissipation.

Table 3 Temperature Distribution for various configurations of gas turbine blades

Materials	8 Holes	12 Holes	16 Holes
Temperature Distribution at 800°C			
Ti-T6	717.71	669.94	567.73
Haynes 188	754.04	725.72	660.20
X-40	769.67	750.50	704.61
Temperature Distribution at 1000°C			
Ti-T6	896.55	836.5	708.01
Haynes 188	942.22	906.63	824.27
X-40	961.87	937.78	880.08
Temperature Distribution at 1200°C			
Ti-T6	1075.4	1003.1	848.3
Haynes 188	1130.4	1087.5	988.33
X-40	1154.1	1125.1	1055.6
Temperature Distribution at 1400°C			
Ti-T6	1268.1	1190.6	1021.9
Haynes 188	1318.6	1268.4	1152.4
X-40	1346.3	1312.3	1231.0
Temperature Distribution at 1600°C			
Ti-T6	1433.1	1336.2	1128.9
Haynes 188	1506.8	1449.3	1316.5
X-40	1538.5	1499.6	1406.5

Haynes 188 performed moderately well, while X-40 retained the most heat, showing the least effective thermal response. The thermal analysis conducted at 1400°C reinforced the influence of cooling hole conFigureurations on temperature regulation in gas turbine blades. Results confirmed that increasing the number of cooling holes consistently reduced blade temperatures, highlighting the effectiveness of enhanced cooling strategies. Ti-T6continued to outperform the other materials by maintaining the lowest temperature levels, demonstrating excellent thermal dissipation. Haynes 188 showed moderate performance, while X-40 consistently retained the most heat, indicating less efficient thermal conductivity. At the maximum temperature of 1600°C, Ti-T6continued to exhibit superior heat dissipation capabilities, maintaining the lowest temperatures among the materials tested. Haynes 188 performed moderately well, while X-40 consistently showed the highest temperature retention, indicating a relatively lower thermal conductivity. The analysis of total deformation across different materials Ti6, Haynes 188, and X-40 under varying numbers of cooling holes reveals distinct structural behaviors (Table 4).

Table 4 Structural Analysis in Total Deformation (m)

Material	8 Holes	12 Holes	16 Holes
Ti-T6	2.0857e-5	2.1356e-5	2.1567e-5
Haynes 188	1.1094e-5	1.1358e-5	8.8461e-6
X-40	1.1147e-5	1.1412e-5	8.8883e-6

Ti-T6shows a consistent increase in deformation as the number of holes rises, indicating a greater sensitivity to structural weakening due to added perforations. Conversely, Haynes 188 and X-40 exhibit a slight increase in deformation with initial increases in hole numbers, but then show a decrease in deformation as more holes are introduced. This trend suggests that Haynes 188 and X-40 may achieve better load redistribution at higher levels of perforation, potentially enhancing structural stability [24]. Haynes 188 in particular has the least deformation exhibiting the best structural stability. The values of equivalent strain obtained using structural analysis of Ti-T6, Haynes 188, and X-40 under varying numbers of cooling holes are shown in Table 5.

Table 5 Structural Analysis in Equivalent Strain

Material	8 Holes	12 Holes	16 Holes
Ti-T6	1.0957e-4	2.0673e-4	2.1513e-4
Haynes 188	1.1001e-4	1.1066e-4	1.1264e-4
X-40	1.1054e-4	1.1118e-4	1.1318e-4

Ti-T6shows a pronounced increase in equivalent strain as the number of holes increases, indicating a higher tendency to deform under applied loads and a lower resistance to strain-induced weakening. On the other hand, Haynes 188 and X-40 exhibit a more gradual and moderate rise in strain, suggesting greater structural stability and better resistance to deformation despite increased perforation. The strain induced is least in Haynes 188, in particular, is the least among the other two materials. These results underscore the importance of carefully considering material strain behavior when designing components with multiple perforations. Such insights are essential for selecting materials that maintain structural integrity in applications like gas turbine blades, where mechanical performance is critical under high thermal and stress conditions. Table 6 shows the equivalent stress values obtained by FEA analysis of Ti-T6, Haynes 188, and X-40 under varying hole conFigureurations. Ti-T6 exhibits fluctuating stress values, showing an initial decrease followed by an increase as the number of cooling holes rises. A similar trend is observed in Haynes 188, with a slight reduction in stress before increasing at higher levels of perforation. In contrast, X-40 maintains a relatively stable stress pattern, experiencing only minor variations despite changes in the number of holes.

Table 6 Structural Analysis in Equivalent Stress (N/m^2)

Material	8 Holes	12 Holes	16 Holes
Ti-T6	2.3210e7	2.2900e7	2.4045e7
Haynes 188	2.3004e7	2.2907e7	2.3486e7
X-40	2.3054e7	2.2917e7	2.2886e7

These findings highlight that Ti-T6and Haynes 188 are more sensitive to changes in hole configurations, potentially affecting their structural performance under stress. Meanwhile, X-40's consistent stress behavior suggests better adaptability to perforation without significant compromise in stress distribution.

Across all temperature ranges, increasing the number of cooling holes consistently reduced the metal temperature, confirming the effectiveness of enhanced convective heat transfer. Among the materials, Ti-T6showed the lowest blade temperatures at every operating point, which can be attributed to its lower density (4.43 g/cm^3) and moderate thermal conductivity (7.2 W/m·K). The lower thermal mass allows Ti-T6to respond quickly to cooling air, resulting in greater temperature reduction. In contrast, Haynes 188 and X-40, with higher densities (9.14 g/cm^3 and 8.3 g/cm^3, respectively), retained more heat due to their greater thermal mass [25]. Their higher thermal conductivities (10–12 W/m·K) did not offset this effect, since the thicker cross-sections surrounding the holes slowed the net dissipation of heat. Consequently, while Ti-T6demonstrates superior thermal efficiency, Haynes 188 and X-40 tend to operate at higher equilibrium temperatures. The structural analysis revealed that Ti-T6exhibited the highest displacement values, which can be linked to its relatively low elastic modulus (110 GPa) and higher coefficient of thermal expansion (8.6×10^{-6}/°C). These properties make Ti-T6more susceptible to dimensional changes under thermal gradients, explaining the observed increase in deformation with additional perforations. In contrast, Haynes 188 and X-40, both cobalt-based alloys with a much higher modulus (220 GPa), showed significantly lower deformation, with values nearly 50% lower than those of Ti-T6. Their structural rigidity enabled better load redistribution even when the number of holes increased, explaining the slight reduction in deformation at higher perforation levels.

The equivalent strain results further reinforce these findings. Ti-T6exhibited the steepest increase in strain with hole count, consistent with its lower stiffness and reduced resistance to thermal expansion. Haynes 188, with its remarkable ductility (elongation ~51%), accommodated local stress concentrations around the holes more effectively, resulting in the lowest strain values among the three materials. X-40, with moderate ductility (20% elongation), showed slightly higher strains than Haynes 188 but maintained good stability compared to Ti-T6. The equivalent stress results showed relatively small variations across the three materials, but the trends provide additional insight. Ti-T6and Haynes 188 displayed fluctuating stress values as hole numbers increased, reflecting sensitivity to stress concentration around perforations. This sensitivity arises because their yield strengths differ significantly (830 MPa for T6 vs. 410 MPa for Haynes 188), influencing how each alloy redistributes loads near weakened sections. X-40, by contrast, demonstrated a more uniform stress distribution, suggesting that its mechanical balance (yield strength ~600 MPa, tensile strength ~750 MPa, and modulus of 220 GPa) allows it to resist localized stress amplification even as perforations increase [26].

Overall, these results highlight a critical trade-off between thermal and structural performance. Ti-T6provides superior heat dissipation, making it effective in reducing operating temperatures, but its lower stiffness and higher thermal expansion make it structurally less reliable under prolonged high-temperature loading. Haynes 188, while retaining slightly higher blade temperatures, offers excellent structural stability due to its high modulus, strength, and ductility, which limit deformation and strain growth. X-40 provides a balanced performance, with moderate cooling ability and consistent stress distribution, making it a promising candidate for applications where both durability and thermal resistance are required.

While Ti-T6shows excellent thermal dissipation in simulations, its practical application is limited by high-temperature instability. Titanium alloys, including Ti-6Al-4V, begin to degrade above 600–650 °C due to oxidation, phase instability, and loss of strength. Although this study extended analysis up to 1600 °C for comparison, in practice Ti-T6requires thermal barrier coatings (TBCs) or surface treatments, and even then, remains unsuitable for prolonged use in the hottest turbine stages [27,28]. Its role is therefore restricted to cooler compressor or low-temperature components. In contrast, Haynes 188 and X-40, being cobalt-based superalloys, offer superior resistance to oxidation and creep but also degrade beyond 1200 °C, necessitating advanced coatings. TBCs lower effective metal temperature by 100–200 °C, but introduce challenges such as spallation, thermal mismatch, and added maintenance. These constraints emphasize that material selection must consider both intrinsic properties and protective systems. Ti-T6is viable only with significant enhancements, while Haynes 188 and X-40 remain more practical for high-temperature blades, particularly when combined with modern TBC technologies.

6.0 VALIDATION

To enhance the credibility of the numerical findings, validation was performed by comparing the results of one representative conFigureuration (12-hole blade at 1200 °C) with published literature. The predicted temperature distribution in the present study showed a clear axial gradient, with higher values at the leading edge and lower temperatures near the trailing edge, consistent with the trends reported by Ayaal et al. [14] and Horlock et al., [13]. The observed temperature drop of approximately 180–200 °C across the blade span with 12 cooling holes closely aligns with the reductions of 150–220 °C reported in these studies for similarly cooled blades. Furthermore, the stress distribution obtained in the present analysis, which highlighted stress concentrations near hole edges and root fillets, is in agreement with earlier FEA-based investigations by Deepanraj et al. [4] and Bhatti et al. [6]. These comparisons confirm that the simulation framework adopted in this work reproduces both the magnitude and location of critical temperature and stress fields reported in the literature, thereby reinforcing the reliability of the present results despite the absence of direct experimental validation.

7.0 CONCLUSION

This research presented a comparative thermal and structural analysis of gas turbine blades made of Ti-T6, Haynes 188, and X-40 alloys under different cooling hole configurations (8, 12, and 16 holes) across a wide operating temperature range (800–1600 °C). The results demonstrated that increasing the number of cooling holes significantly reduces blade temperatures for all materials. Ti-T6consistently exhibited the lowest blade temperatures due to its lower density and thermal mass, which enhance cooling effectiveness. However, Ti-T6also showed the highest deformation and strain, a consequence of its relatively low elastic modulus and higher coefficient of thermal expansion, indicating limited structural stability at elevated temperatures. Haynes 188 and X-40, in contrast, retained more heat but displayed superior structural integrity, with lower deformation and more stable stress distributions. Among the three, X-40 offered the most balanced performance, combining moderate cooling efficiency with strong mechanical stability, making it a promising candidate for advanced turbine applications.

Despite these insights, certain limitations of this study must be recognized. The material properties used in the finite element simulations were assumed to be temperature-independent within each load case, whereas real materials undergo significant property degradation at high temperatures. The analyses were restricted to steady-state conditions, whereas actual turbine blades experience complex transient thermal cycles, creep, oxidation, and fatigue damage. Simplified boundary conditions were adopted for coolant convection and gas-side heat transfer, which may not fully capture the Multiphysics interactions in service. Furthermore, the role of thermal barrier coatings, which are essential in modern turbines, was not explicitly modeled.

8.0 FUTURE WORK

Future work should therefore extend this study by including temperature-dependent material behavior, creep–fatigue interaction models, and oxidation kinetics for improved prediction of long-term durability. Coupled CFD–FEA approaches can capture more realistic film cooling and fluid–solid interactions. Experimental validation, either through coupon-level tests or scaled blade prototypes, will be crucial to corroborate simulation trends. Finally, the investigation can be expanded to include advanced nickel-based superalloys, ceramic matrix composites, and thermal barrier coating systems, which together represent the practical direction of next-generation turbine blade technologies.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper

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