Relative Stress Analysis of Gas Turbine Blade for Various Alloying Materials

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Abstract. Gas turbines provide a reliable and efficient production of power in both pilot power plants and aircraft propulsion. The operating cost of the modern gas turbines is greatly influenced by the durability of hot section components. To cope up with the increasing temperature, there has been an evolution of new generation blade materials. At elevated temperature conditions, thermal stress and resulting deformations can affect the power developed and efficiency. In this paper a finite element simulation has been made on a fixed blade profile to explore various factors affecting the turbine blade. Variety of existing and new generation materials have been considered under a boundary condition of constant high pressure and high Operating temperature was varied between 1000°C-1400°C. The development of stress and deformation along with the heat flux have been studied for finding the most effective manufacturing alloy for gas turbines.

1. Introduction
The gas turbine has emerged as an effective and efficient means of power generation in several industries, especially in aircraft propulsion and land-based power generation. Gas turbine is also found to be a sustainable power head, which can produce relatively more energy per unit size and weight. With the increasing temperature and pressure through the compressor section and further in the combustion chamber, there is a probability of failure of turbine blades which are supposed to face the highest temperatures and corresponding thermal stress. From the thermodynamic analysis of gas turbines using a Brayton cycle, it is evident that the increase in pressure ratio increases the thermal efficiency of the gas turbine along with an increase in Turbine Entry Temperature. Griffin & Kumar [1] made an investigation on the composition of gas turbine blades which shows that the stresses plays a central role in the study of the material efficiency of the gas turbine blade and also an observation was made for the distortion which gently enhances from root to the tip section of the turbine blade at some extreme temperature and pressure condition. Dhamecha et al. [2] scrutinizes the failure of the gas turbine blade through finite element software. The results demonstrate that the least strain is at the origin section of the blade and highest strain is at the tip section, and the maximum stresses were observed closer to the root section of the turbine blade and also nearer to the cooling holes. S. Gowreesh et al. [3] researched about the first-stage rotor blade of a two-stage gas turbine that has been analysed at various temperature distribution for structural and thermal analysis. Further an analysis was done on finding the maximum efficiency condition of the blade. A study was done to analyse the thermo-elasto-plastic stress and strain on turbine blade according to a typical loading spectrum. Controlled-strain test of turbine blade material was performed which concluded with several points on the turbine blade to be most efficient for fatigue, and also resulting to some exact fatigue spot on the blade surface [4].
Brahmaiah & Kumar [5] analysed about four different gas turbine blade models with and without holes and studied the consequence of substituting different number of holes on the blade’s behaviour. The outcome of temperature spread and shift showed that the blade with highest number of holes was considered as the best option. They performed the analysis for two materials chromium steel and Inconel- 718 for their research, it was observed that the Inconel with induced stresses, is lower than the chromium steel with a better thermal characteristic. Steady state thermal analysis of gas turbine rotor blade was also investigated by Laihtwe et.al [6]. Their results demonstrated that the total heat flux for copper, titanium and nickel primarily depends on the convection heat transfer coefficient and thermal conductivity of the material. Structural and thermal analysis of turbine blades with a variety of temperature was studied by Kundu et al. [7]. The present work demonstrates the structural behaviour of such blades with cooling channels under their operational temperature for variety of blade materials like Titanium Alloy, Steel alloy, Magnesium alloy (AZ31B) and Aluminium alloy (6061 T6), to study the induced stress, heat penetration and resulting deformation.

2. Blade modelling and material properties under analysis

The gas turbine blade is revealed to different range of temperature and the respective consequences are taken into consideration. Stress analysis is performed to know the Various action of stress and strain on variety of alloys at different exposed temperatures. In this project, a comparative analysis was done for different mechanical parameters affected due to the application of different temperature at a fixed boundary condition. The blade profile dimensions were taken as per NACA-0012 AIRFOIL [8]. A three-dimensional model of the turbine blade with cooling holes have been created as shown in (figure1). A finite element analysis package has been used to evaluate the variation of stress, strain and deformation across the turbine blade. The bounding box diagonal is $2.60 \times 10^{-3}$ m$^2$ and the average surface area is $3.17 \times 10^{-7}$ m$^2$. Five different materials were applied for this analysis, which includes Titanium Alloy, steel alloy, Magnesium alloy and Aluminium Alloy which are widely used to manufacture the gas turbine blades and their properties listed in table.1. AZ31B is a wrought magnesium alloy which has various implementations in the field of aircraft fuselages and concrete tools due to its better ductility.
and weldability. E-Glass composite has been selected as a possible alternative material and checked for its applicability in such high temperature environment. To understand the parametric behaviour of the blades, simulation was done in the range of temperature between 1000°C to 1400°C.

| Table 1. Materials details |
|---------------------------|
| Material | Density (kg/m³) | Young’s Modulus (×10⁴ MPa) | Poisson Ratio |
| Ti alloy | 4620 | 9.6 | 0.36 |
| Steel alloy | 7850 | 20.0 | 0.3 |
| Mg Alloy AZ31B | 1775 | 4.5 | 0.31 |
| Al Alloy 6061 T6 | 2713 | 6.9 | 0.33 |
| E Glass-composite | 2600 | 7.3 | 0.22 |

3. Analysis of simulation results
The solution from the computational analysis of the blade was recorded in the form of various parameters like maximum stress, deformation, maximum strain and total heat flux. Out of all these materials Ti alloy has showed the capacity to tolerate the maximum temperature with minimum deformation compared to the other materials at same conditions. The analysis for all the alloys were done at three different ambient gas temperatures i.e. 1000°C, 1200°C and 1400°C. The blades of the turbine were designed with different materials and followed by analysing consequently with same maximum pressure as ambient conditions.

3.1. Structural and thermal analysis of blade profile for various alloys
The magnesium alloy AZ31B can be applied at high temperatures to produce a wide variety complex component which can be used in automotive industry. Analysis of this alloy has been performed at various temperatures as a gas turbine blade material. From figure 2(a) it is observed that the principal stress is maximum close to the hub whereas comparatively lower throughout the other surfaces. This material also shows the highest deformation at the highest temperature of 1400°C. So, the material is a bit unfit in comparison with other alloys which shows development of lesser deformation. Surve [9] also found higher value of deformation in similar analysis for magnesium alloy under fixed tangential axial and centrifugal forces. Therefore, AZ31B Alloy containing more percentage of magnesium, happens to be less beneficial than its counterparts.

![Figure 2](image-url) Results of structural and thermal analysis of Mg Alloy AZ31B at 1400°C
(a) Maximum principal stress (b)Maximum shear stress (c)Total Deformation (d)Total heat flux
Aluminium alloy 6061-T6 is an average strengthened heat bearable material. It has a fine resistance towards corrosion, and it is also superior to weldability in spite of reduced strength in the weld zone [10]. The analysis of this alloy at different temperature gives comparatively less stress and strain development with increasing temperature in comparison to AZ31B. From figure 2 & 3 it is evident that the principal stress is maximum, close to the root of the blade and extending towards the tip. Also, from figure 3(c) we got the maximum and minimum deformation of the blade towards the tip and root of the blade respectively. So, this analysis shows the fact that 6061-T6 is more efficient to be a blade material than Mg Alloy AZ31B.

Comparative study of the deformation between titanium alloy and steel alloy carried out at same boundary conditions, has been presented in figure 4 and 5. The principal stress as shown in figure 4(a) is observed to obtain an average value after the simulation whereas in figure 4(b) the stress is maximum towards the hub in case of steel alloy at 1400°C. It was also observed that in this case the maximum stress covers a lesser area than the other four materials. The maximum deformation has been also compared in figure 5. Where Ti alloy shows the least deformation of $1.45 \times 10^{-5}$ m at 1400°C. So, Ti alloy is found more efficient as a blade manufacturing material.
3.2 Investigation on the applicability of E-Glass as a blade material

Glass-fibre-reinforced composites have been used on military aircraft’s structural application for more than five decades. Although more popular in wind turbines, the behaviour of this new generation composite material has been tested in literature as transition duct material in gas turbines [9]. Therefore, an investigation has been done to check the applicability of E-Glass as a blade material in this work under similar operating conditions. The observations are depicted in Figure 6 which shows much lesser stress and deformation under maximum temperature. E glass can be considered as one of the options for the gas turbine blades if its other properties can be controlled.

![Figure 6. Behavior of E-Glass at elevated temperature](image)

(a) Maximum principal stress at 1400°C (b) Total deformation at 1400°C

3.3 Comparative study of various blade materials at variable temperatures

The present investigation also shows the comparison of all the investigated materials at the same range of temperatures. In the analysis of different alloys at various temperatures maximum shear stress was found closer to the hub of the blade in all the cases. So, this force is basically tending to cause the deformation of the turbine blade. Also, due to the given geometry a stress concentration is generated which may lead to a crack or bending of the geometry. Thus figure 7 represents the effect of temperature on maximum shear stress for five different materials which showed minimum stress for Ti alloy and E-Glass composite in the range of 1000-1400°C. On the other hand the deformation is observed to get enhanced from the root to the tip of the blade, which gives the maximum deformation at the tip of the blade. Hence, figure 8 represents the effect of maximum deformation with varying temperatures where Aluminium based alloys perform better. The comparison of maximum principal stress (figure 9) showed the maximum stress development for steel alloy. For all cases, E Glass composite was found to appear as a good option with respect to the present analysis.

![Figure 7. Effect of Temperature on Maximum Shear Stress](image)
4. Conclusion

In this paper an analysis of stress, strain, heat flux and deformation are done at temperature ranging from 1000-1400°C. From the simulation result, it can be concluded that Ti alloy shows minimum deformation and strain than other materials at the highest temperature. At the same time, steel alloy is showing the major deformation, proving to be the most unfit material. Comparing the analysis of the current study, is able to conclude that the most effective material is Ti alloy. Maximum principal stress and maximum shear stress is also found low in Ti alloy compared to the other four materials. More analysis can be fruitful to gain confidence on the behaviour analysed in the present work.

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