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Analysis of Creep Behavior in Turbine Blade Made of Nickel based Super-alloys with Coating of Ceramic Matrix Composites

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Abstract

Creep is a hazardous phenomenon, predominant in components subjected to extreme working conditions such as high temperatures and loads. It is responsible for the formation of primary cracks in components, which ultimately leads to the failure of entire component. The blade materials in gas turbines are subjected to creep during operating conditions. The creep behavior of turbine blades made of Nickel (Ni) based super-alloys, subjected to high temperatures and mechanical loads are analyzed. The Bailey-Norton model is used to characterize the creep behavior of the blade. Usually, ceramic matrix composites (CMC) are materials with better creep resisting properties compared to other materials. In this study, Silicon Carbide (SiC) fibers reinforced in SiC matrix are used as a coating for Ni based super-alloys to reduce the creeping behavior. The influence of CMC coating on attenuating the creep deformation of the turbine blade is studied. A comparative study is made between the alternative materials used for turbine blades, to find an optimal material in terms of creep life for gas turbine.

Keywords

Creep, Turbine blade, Ceramic matrix composites, Power law, Inconel

Introduction

Creep phenomenon is hazardous for mechanical and electromechanical components, connections, networks and devices, which find use in high temperature and rough environment applications over a prolonged period of time. During creep, inelastic deformation occurs over time in a material when it is continually subjected to stress. Creep occurs below the yield strength and becomes more severe with higher temperatures and stresses. It plays a major role in moving parts, including turbine rotor components. The turbine blades in gas turbines are subjected to high temperature and structural loading during various cycles of operation. Generally, creep is observed when the operating temperature is about 0.4 to 0.6 times the absolute melting temperature of the material considered.

Material creep behavior is composed of primary, secondary, and tertiary phases. When either the operating temperature or stress increases, the creep strain rate in the primary and secondary stages increases. Also, the tertiary phase accelerates resulting in a reduced life leading to stress rupture. This is primarily due to the increase in the mobility of atoms with an increase in temperature resulting in material diffusion which helps in further dislocation of atoms. Diffusion still can occur at grain boundaries and phase interfaces at lower temperatures. Also, the temperature beyond which the creep behaviour will be prominent varies with materials.

CMCs are at the forefront of advanced materials technology. Research has been concentrated on fiber reinforced ceramics over the years, as opposed to monolithic materials. It possesses adequate strength at high temperatures but with the drawback of poor impact resistance. These composites are preferred over other materials because of their very good properties such as, low density, high strength, high fracture toughness, high fatigue, and creep resistance, in addition to chemical inertness, high thermal and corrosion resistance. SiC fibers reinforced in a ceramic matrix made of SiC or Alumina are the commercially available CMC in today's scenario, due to the fact that these materials are capable of operating at temperatures up to 1200 °C. To utilize the ultimate load carrying capabilities at high temperatures, single crystal oxide fibers are preferred.

Inconel, Palladium alloy, and Titanium alloy have been used as material for making jet turbine blade. Based on the structural analysis at higher temperature, Inconel 718 was considered the better material over Titanium T6 [1]. A new material Ni based super-alloy was proposed to replace Nimonic alloy 80A and Inconel 625 for gas turbine application due to its reliable service life [2]. Chermant et al. [3] have shown that the creep of CMCs reinforced with continuous ceramic fibers is controlled by damage creep mechanism and primary creep was found to be significant depending on fiber microstructure. The damaging process can be divided into two stages, micro-crack formation and microgroove growth, the latter leading to formation of pores. Steady-state creep was basically shown as a result of grain-boundary sliding [4]. The SiC-based fibers are more creep resistant than the oxide fibers.

Vera et al. [5] studied the high temperature compressive strength and creep behavior of fiber bonded SiC material obtained by hot-pressing of Si-Ti-C-O fibers. The deformation mechanism and onset of plasticity was evaluated and compared with other commercial SiC materials. A transient viscous creep stage was observed due to flow in the silica matrix and determined the stress exponent and activation energy. Failure due to creep is an important mode of failure in turbine blades. Liu et al. [6] proposed a numerical approach for assessing the life of turbine blades, based on the Lemaitre-Chaboche creep damage model.

A sensitivity analysis on the parameters affecting the temperature and life of high pressure and temperature first stage turbine blade was carried out [7]. The significant parameters observed were blade coating thickness and coolant inlet pressure. Creep deformation and rupture experiments were conducted at 649 °C and 982 °C by Stewart et al. [8] on the Ni-based super-alloy directionally solidified GTD-111. The secondary creep constants were analytically determined from creep deformation experiments. Using regression analysis, the secondary creep constants are determined for discrete temperature values. Abdulah et al. [9] studied the stress-strain behavior and deformation produced by the centrifugal force on a turbine blade, along with the behavior of their natural frequencies. The material chosen were Ni based super-alloys In-738 and GTD-111. It was shown that the alloy GTD-111 is better for manufacturing blades.

Methodology

A 3D model of gas turbine blade was created in Solidworks and the numerical simulation was carried out using ANSYS. The steady state thermal analysis is performed to understand the temperature distribution and heat flux field across the blade's profile. The static structural analysis is performed to understand the creep behavior in the turbine blade for different materials (Table 1). The results obtained are used to determine the most suitable material for the gas turbine blade. It is assumed that the material shows the same creep and long-time rupture behavior under compressive load as in the tensile load, apart from the sign of the creep strain. The thermal load is applied on the entire blade geometry for this study.

Creep models

For this study, the creep model that is considered for the analysis is the Norton's power law model (Eq. 1), which is the widely accepted constitutive equation for predicting the secondary creep, which is of our interest. Hi-Nicalon Type S SiC fiber reinforced in SiC CMC along with Ni-based super-alloys such as Inconel 718, Nimonic 80A, and GTD 111 are the materials considered for the analysis. Based on extensive literature review, the creep constants for different materials taken for this study are provided in table 2. The materials selected exhibit superior mechanical behavior at higher operational temperatures and have a high melting point temperature. Hence, these materials are prime candidates for making major engine components such as turbine blades.

$$\varepsilon_{cr} = A\sigma^{n} e^{-m/T} \quad (1)$$

Numerical modeling of turbine blade

A 3D CAD model of the turbine blade was made using Solidworks 2022. For analysis purposes, single blade geometry

Table 1: Properties of turbine blade materials.

Materials	Yield Strength	Young's Modulus of Elasticity	Poisson's Ratio	Density	Thermal Expansion Coefficient	Specific Heat	Thermal Conductivity
	(MPa)	(GPa)		(kg/m³)	(x 10^{-5} m/m)	(J/kgK)	(W/mK)
INC 718	9804	165	0.3	8220	1.54	550	22
NIM 80A	780	183	0.3	8190	1.57	610	21.5
GTD 111	825	130	0.33	8300	0.90	460	16
SiCf - SiC	560	410	0.2	3120	0.40	740	105

Table 2: Creep properties of turbine blade materials.

	A ($s^{-1}Pa^{-1}$)	n	m
INC 718	2.14E-70	10.171	50826
NIM80A	1.02E-64	6.2	50998
GTD111	2.77E-50	7.5	0
SiCf - SiC	1.88E-18	1.3	0

is considered (Figure 1), due to the rotational symmetry. The blade model from Solidworks is imported to ANSYS and it was divided into 3 parts namely, blade, body, and root. This was performed to apply different thermal loads on each body as there is temperature gradient along the blade. Once the changes in the geometry were made, it was meshed in ANSYS. The blade temperature distribution can be obtained by performing the steady-state thermal analysis along with heat flux on the blade. This is applied as a body force in static structural analysis. The loads acting on the blade are mentioned as boundary conditions in the solution setup section. The meshed model of the turbine blade is composed of 50604 nodes and 30810 hexahedral elements (Figure 1).

A gas turbine blade is subjected loads from different sources. For the purpose of this study, the gas turbine blade is considered to be a cantilever beam and is fixed at one end (root of the turbine blade) and the loads due to rotation, heat, hot gases, and pressure have been applied as mentioned in table 3.

Results and Discussion

Validation study

The simulation procedure used for the present study is validated by comparing the deformation of turbine blade under thermo-structural analysis with published results available in literature [2]. The material considered for the validation study is Nimonic alloy 80A. The deformation obtained in turbine blade for 9000 rpm rotational speed from the present study is 2.01 mm, which is closer to the published results (2.18 mm). The deformation is observed to increase with rotation speed.

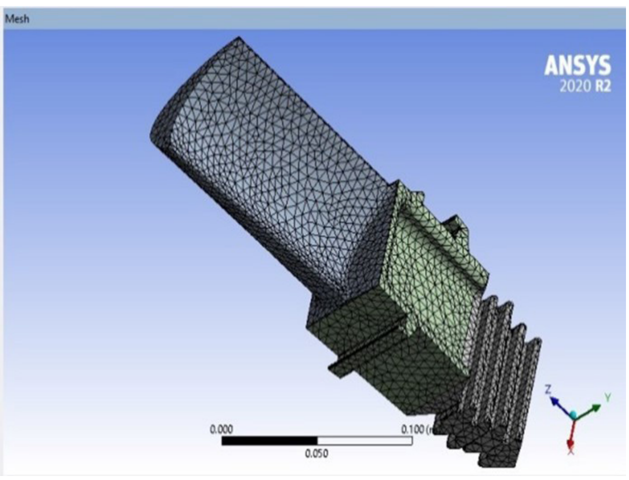


Figure 1: Meshed turbine blade.

Table 3: Loading conditions.

Load	Value	Location
Rotational velocity	10000 rpm	Centroid of the blade
Temperature	650 °C	Blade airfoil section
	500 °C	Blade body
	350 °C	Blade root
Force due to gas	350 N	Axial force
	1250 N	Tangential force
Pressure	400 kPa	Front face of blade
	150 kPa	Back face of blade

Without CMC coating

The creep simulations were conducted as per the loading conditions mentioned in table 2. The analysis is performed in ANSYS by assigning the materials of turbine blade as Inconel 718, Nimonic 80A, and GTD111DS. From these simulations, the values of deformation, elastic strain, creep strain, and von Mises stress were recorded. The deformations in turbine blades for varying materials are shown in figure 2.

The region where the blade is connected to the body of the rotor is of prime importance. This region is mostly exposed to harsh loading conditions. It acts as source region for formation of micro-cracks which may grow eventually during the operation of the blade causing failure of the blade. This in turn leads to the failure of the gas turbine. Therefore, this region is focused in the present study. The deformation obtained on the turbine blade for different materials is provided in table 4. The maximum and minimum deformation, under the same loading conditions occurs in INC718 and NIM80A materials respectively (Figure 2a and 2c). The total deformation obtained here

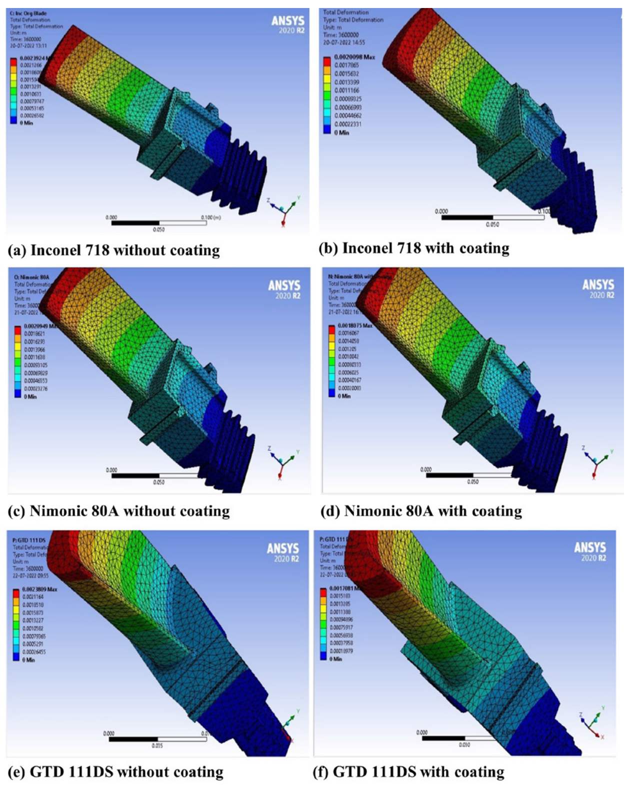


Figure 2: Deformation in turbine blade made of different materials.

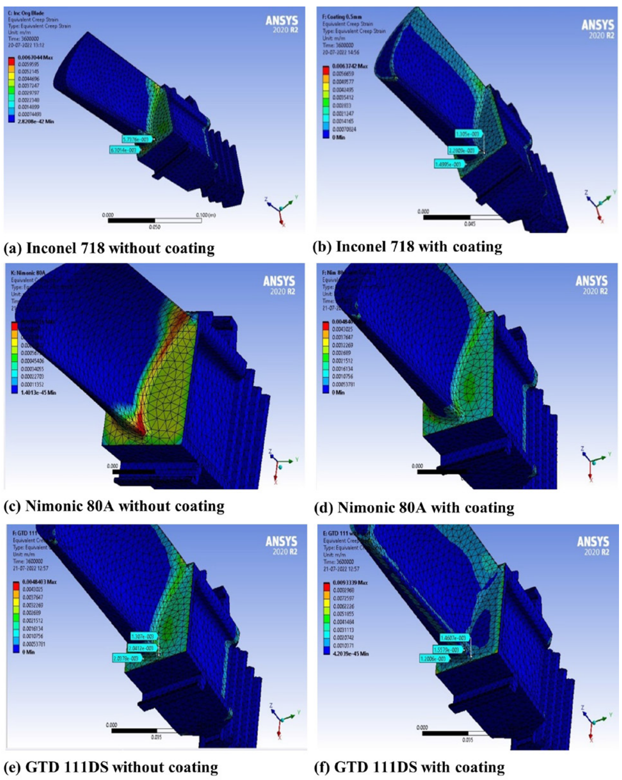
Table 4: Maximum values of creep strains.

Parameter	Material	Without CMC Coating	With CMC Coating
Deformation (mm)	INC718	2.39	2.01
	NIM80A	2.09	1.81
	GTD111	2.38	1.71
Creep Strain (%)	INC718	0.670	0.637
	NIM80A	0.503	0.484
	GTD111	0.484	0.479

is the combined effect of both elastic and creep deformation. 95 percent of deformation occurs in the first load step (elastic loading) followed by slow and continuous deformation during the creep stage.

With CMC coating

A coating of SiCf – SiC, CMC with thickness 0.5 mm was applied over the base materials considered in this study. Later, the creep simulations were performed with the same loading conditions and the results were noted down. Here, SiCf - SiC CMC was selected as a coating as it is clear from the literature review that it has better creep resistance at elevated temperatures. The values of elastic and creep strain were found to be reduced in the region of interest after the application of the CMC. The reason for this might be the enhanced creep properties of SiCf – SiC CMC. The strains in that region get redistributed to the surface coating, which can be observed in the contours (Figure 3). Since the CMC coating is highly resistant to heat, it also acts as a thermal barrier coating. It shields the internal blade and reduces the chance of being exposed to harsh conditions, preventing the integrity and strength of the blade. Thus, increases the blade life, enables longer hours of operation and reduction in the maintenance cost of the gas turbine. Also, it can be seen that the deformation of all the blades due to creep was low for blades coated with CMC compared to uncoated blades (Figure 2). Similarly, reduction of creep strain is also observed upon coating the blades with CMC (Figure 3). The blade made of INC718 super-alloy had the highest deformation of 2.39 mm and CMC coated GTD 111 DS blade had the least deformation of 1.71 mm. Therefore, GTD111DS material has the least deformation and creep strain with CMC coated on it.



(a) Inconel 718 without coating (b) Inconel 718 with coating (c) Nimonic 80A without coating (d) Nimonic 80A with coating (e) GTD 111DS without coating (f) GTD 111DS with coating

Figure 3: Creep strain in turbine blade made of different materials.

Conclusion

A lot of improvements in the field of CMC are taking place and emphasis is given to development of new CMC capable of operating at high temperature applications. The feasibility of using CMC in the gas turbine blades is studied, to improve the lifetime. In this study, existing Ni based super-alloys were used for simulating the creep deformation behavior of turbine blade. CMC coating to Ni based super-alloys not only reduces the deformation and creep, but also distributes the stress leading to lower stress concentration. This in turn increases the service lifetime of turbine blades. It is observed that Nimonic 80A super-alloy is a better choice as it deforms less when compared to other materials used for turbine blades among the materials considered in the study. Upon using CMC coating, it is found that GTD 111 has better resistance to deformation and creep strain.

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None.

Conflict of Interest

The authors declare no conflict of interests that are relevant to the content of this article.

Credit Author Statement

R. Naveen: Conceptualization, Methodology, Investigation, Formal analysis, Writing - original draft preparation; Jithin: Inferences, Writing - original draft preparation, Writing - review and editing; N. Rino Nelson: Conceptualization, Methodology, Investigation, Formal analysis, Writing - review and editing, Supervision. All the authors read and approved the manuscript.

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