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An Investigation of Transient Thermal Analysis of 1st Stage Gas Turbine Blade Manufactured by Directional Solidification and Mechanically Alloyed Nickel-Based Superalloys

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Abstract

The turbine rotor blades of a gas turbine engine are designed for operation at elevated temperatures, particularly first stage gas turbine blades. During operation, the turbine blades are subjected to high temperatures and large centrifugal forces. In addition to these, the temperature variations occur at start-up and shutdown cycles of the engine. Due to sudden changes in temperature, transient thermal effects are sighted and time-dependent temperature gradients appear. The estimates of the thermal variations sighted on the turbine blade at various operational speeds of the gas turbine rotor are important in determining the fatigue life. The thermal condition during the startup sequence initiated is considered as a major factor in determining the rotor maintenance interval and individual rotor component life. This work has primarily focused on transient thermal stresses arising in the rotor blade by using Finite Element Analysis. Nowadays, the thermal stresses of the gas turbine parts are determined by user defined software's that is based on numerical methods which are being used significantly. A typical turbine rotor blade has been modeled by using CATIA V5R21. Turbine blades are made of Nickel-based superalloys have been selected for transient thermal analysis by using ANSYS 15.0. Comparative analysis has also been carried out to determine the suitability and strength of turbine blade material under the same operating conditions. Two blade materials such as IN 792 DS and IN 754 MA have been selected for comparative analysis and these blades were manufactured by Directional solidification and mechanical alloying methods respectively. The physical and mechanical properties are updated to the model and appropriate boundary conditions are applied. Thermal stresses are evaluated for both materials and the results have been compared with IN 738 LC. Static analysis has also been carryout out to examine the structural performance of the alloys. It has been observed that maximum stress and strain are sighted near the root of the turbine blade. The temperature gradients sighted on the turbine blade during acceleration and decelerations are below the melting temperature of the blade materials. It has been noticed that the transient thermal stresses are higher than the steady state thermal stresses. It has been observed that IN 792 DS has better physical and thermo mechanical properties that can withstand higher turbine inlet temperatures and could be suitable material for the manufacturing of turbine blade at Marine and Related Environments.

***Keywords:** Transient thermal analysis, Gas turbine blade, Superalloys, Finite element method*

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1. Introduction

Transient thermal analysis is a relatively a new technique and is being applied to some aero and marine gas turbine engines. A transient condition said to be when condition parameters such as speed, firing temperature and load varying with time. Start-up and shutdown are transient events when there is a change in load or an acceleration event. White (1988) has summarized the main differences between steady state and transient conditions. During transient, shaft inertia will either be damaged or produce power (depending on whether it is being accelerated or decelerated). Pressure and temperature gradients occur during transient causing changes in the mass flow rates in and out of components. Dimensions of various components can change due to temperature and centrifugal effects. Tip clearances can be affected. In large critical turbo machines however, problems often develop under transient conditions due to factors such as increase in loading, thermal stresses, changes in tip clearances and changes in thrust position. Several gas turbine operators use transient analysis to measure coast down times or plot start-up curves using strip charts or by trending packages. Besides high turbine inlet temperature (TIT), it is well known that start-up and shutdown cycles affect blade life through thermal fatigue of the structural material this is because of variations in thermal loads. Blade failures in rotating engines may have severe impact on the availability of engines. Therefore, it is observed as an important challenge especially, in gas turbine engines. Blade failures are caused by a number of mechanisms under the turbine operating conditions of high rotational speed at elevated temperatures. These failures may have different causes, such as creep or fatigue damage, external and internal damage of blade tip and turbine casings [1-8]. Turbine blades are the most important components in a gas turbine and are responsible for extracting energy from high temperature gases. The transient behavior takes some time before it attains an equilibrium temperature. During this interim period, the temperature is varied with time and the disk is said to be in transient state. Transient thermal analysis indicates the thermal shocks that are induced in the disk. Thermal shock is produced by transient temperature gradients that are applied abruptly. The temperature gradients that can be established in the transient state are generally higher that those occur in steady state. Due to these reasons there is a great importance in predicting life of a gas turbine blade to with stand at higher elevated temperatures [9].

At design point the gas turbines operate efficiently and safely because all their components are well matched and the flow aligned with the blade passages to avoid losses. Certainly, gas turbines are required to operate at off-design over a wide range of operating conditions, which depends up on the engine applications whether at land, sea or air, both civil and military [10].

During start-up, the rotors that are cold experiences transient thermal stresses as the turbine is brought on line. Large rotors with their longer thermal time constants develop higher thermal stresses than smaller rotors undergoing the same startup time sequence. High thermal stresses reduce thermo-mechanical fatigue life and the inspection interval [11].

1.1. Nickel-based Superalloys

Nickel-based superalloys of directional solidification (DS) for industrial gas turbine blades were developed based on alloy IN 792 with approximately 12 mass % Cr. From preliminary test results a temperature gain in stress-rupture strength of 30 K can be expected, compared to Re-free aero engine alloys with columnar grains. This significant strength improvement can be achieved by adding 2 to 3 mass % Re in the group of 12 mass % Cr alloys. With balanced Cr-, Al-, and Ti- contents they also exhibit superior hot corrosion resistance compared to typical high Al / low Cr / low Ti aero engine alloys.

The present development leads to the optimized and modified alloying concepts; a new DS alloy was developed, IN 792 DS this new alloy exhibits enhanced properties regarding creep strength and castability, combined with good corrosion resistance. Increasing the Al-content above the limit to form an Al_2O_3 scale (*i.e.*, above about 5%) gives rise to catastrophic hot corrosion attack [12].

MA 754 alloy, showing excellent thermal fatigue and high temperature mechanical resistance due to its high stability of Y_2O_3 hardening dispersion, has been adopted for vanes atleast in one application. They are known as Oxide dispersion strengthened superalloys (ODS). ODS alloys are produced by mechanical alloying and contain fine incoherent oxide particles which are harder than the matrix phase [13].

Like other ODS materials, MA 754 alloy has a very fine, flat, log stress-log rupture life slope compared to convectional alloys. The strength of MA 754 alloy is about 100Mpa for 100 hours life, this is somehow higher than the other ODS alloys and several times greater than the conventional materials, like MAR-M alloy 509 and alloy 80 A. Thus, while MA 754 alloy is compared to TD (Thoria dispersed) Ni-Cr, it has a non-radioactive dispersoid and high strength, so it is suitable for the applications such as gas turbine vanes [14].

IN 738 LC has remarkable corrosion resistance and also creep resistance in high temperatures. Creep is known as one of important restrictive options of the gas turbine blade life. The IN 738 LC alloy is commonly used for gas turbine blades are strengthened by precipitation of (γ) phase [15].

1.2. Problem Statement

Previously some work had been carried out on failure of turbine blade through metallurgical and mechanical analysis. Mechanical analysis has been carried out assuming that there might be a failure in the blade material due to blade operation at elevated temperatures and subjected to large centrifugal forces which finally led to the ultimate failure of gas turbine blade. Structural and steady state thermal analysis has been carryout as a part of mechanical analysis [16-19]. An attempt has been made on transient thermal analysis of gas turbine blade. Transient thermal analysis has been carried out for estimation of transient effects on turbine blades for predicting the steps that could be taken for improvement of blade life. Nickel-based superalloys are considered for evaluation of thermal effects that are induced on blade by applying appropriate boundary conditions. The principal forces acting on the blade are observed as gas pressure and force due to change in momentum that enables the rotation, pressure force accompanied by axial and tangential components of the gas flow. Since the turbine rotor is subjected to large temperature variations, the material properties such as Specific heat, Enthalpy and Young's modulus undergo variation with time. In such conditions, there is a probability of failure of the rotor, if the turbine rotor is not designed to withstand at transient event. The convective heat transfer coefficient has been calculated by using the heat transfer empirical relations taken from the heat transfer data book. Therefore the investigation of the transient thermal effects that are sighted at transient regime; Von-mises stress, Total deformation and strain are also calculated to justify the structural stability of the materials, which could be suitable for marine environments [20-23].

2. Background Data

It was reported that the turbine blades under investigation were made up of Nickel-based superalloys IN 792 DS and IN 754 MA and were manufactured by Directional solidification and mechanical alloying methods respectively.

Table 1. Chemical Composition of HPT Turbine Blade Made of Nickel-based Superalloy

Superalloy	Ni	Cr	Ti	Al	Mo	Ta	C	B	W	Zr	Hf	Co	Y_2O_3
IN 792 DS	bal	12.7	3.9	3.4	1.8	4.2	0.012	0.016	4.3	0.03	0.89	8.7	-
IN 754 MA	bal	15.5	2.5	4.5	2.0	1.9	0.06	0.01	-	0.6	-	-	1.1
IN 738 LC	bal	16	3.4	3.4	1.7	1.7	8.5	0.01	2.6	0.10	0.90	0.17	-

Table 2. Physical and Mechanical Properties

Property	IN 792 DS	IN 754 MA	IN 738 LC
Young's modulus(Gpa)	220	228	175
Thermal conductivity (W/m °C)	10	14.3	16.2
Possion's ratio (τ)	0.29	0.27	0.33
Density (Kg/m^3)	8250	8550	8110
Specific heat (J/Kg. k)	460	500	450

3. Modeling of Gas Turbine Blade

Reverse Engineering (RE) is being applied to generate 3D surface data of turbine blade. The data to make real model of a turbine blade is obtained using Coordinate Measuring Machine (CMM). The blade model profile is generated by using CATIA V5R21 software. 3D model of a gas turbine blade with root was done in two stages. These two were then combined to make a single volume using union Boolean operation. Geometric model of gas turbine blade using CATIA V5 R21 is shown in Figure 1.

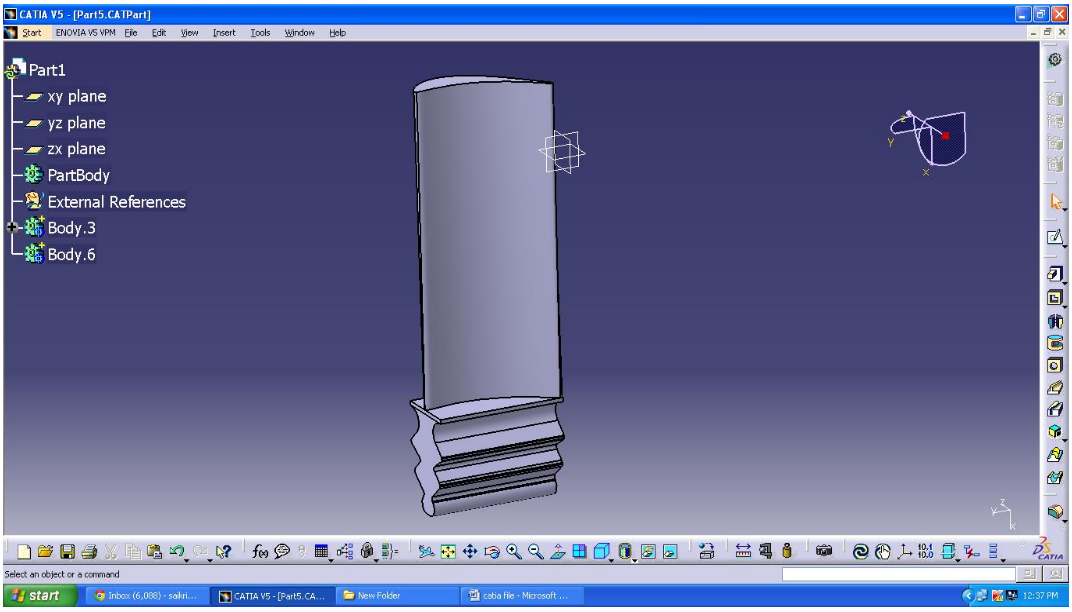

Figure 1. Geometric Model of Gas Turbine Blade Using CATIA V5 R21

4. Design Operating Conditions

Gas Turbine blade operating conditions are considered at transient operation during start-up as shown in Figure 2. Steady state heat transfer coefficients are considered as the initial boundary condition at the start up. Boundary conditions are updated on the model to simulate the actual environment where rotor blades are exposed to high temperature.

Initial temperature turbine is given as 950°C. Ambient temperature is raised from 400°C to 1300°C. Heat flux and convective film coefficients vary with time and temperature, which are calculated by using the following empirical relation for laminar flow over a flat plate [24],

$$Nu = 0.332\ Pr^{1/3}\ Re^{1/2}$$

Bulk temperature ranging at 787.5°C Reynolds number is found in range from 2.0×10^5 - 2.7×10^5. Since $Re < 5 \times10^5$ flow is laminar. Obtained heat transfer coefficients are kept for analysis using ANSYS. The loads acting on blade materials are static loads – axial, tangential by gas pressure and centrifugal load due to rotation.

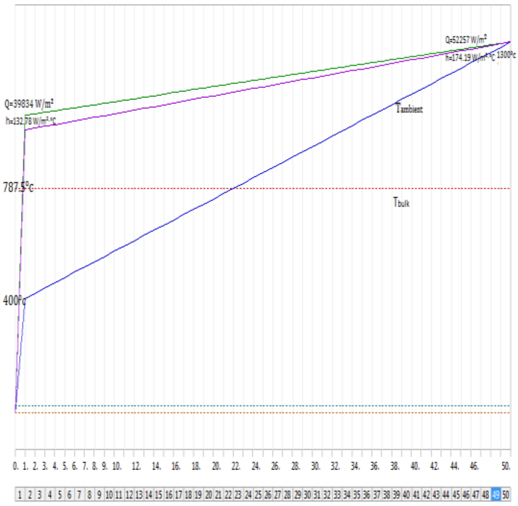

Figure 2. Transient Loading Condition

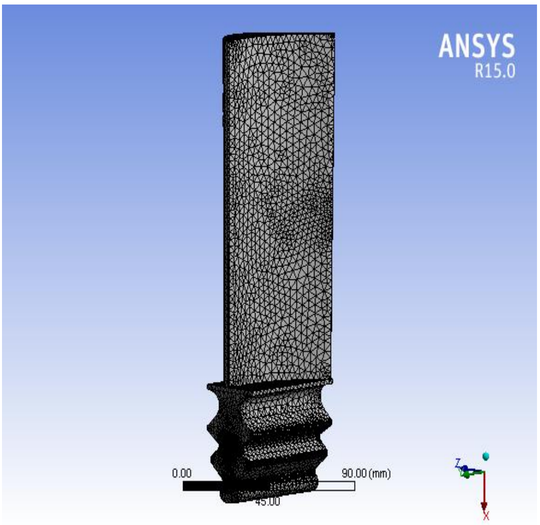

Figure 3. Meshing of Turbine Blade

4. Finite Element Method

Finite element analysis is run by taking the geometry of a component and splitting it into a number of elements. Each element is then given a material property (such as Young's modulus and thermal conductivity) and is connected to other elements by nodes as shown in Figure 3. Test conditions such as load and temperature are applied and the model is run in a number of small time steps. Since the conditions at points within each element are varied for each time step, the equations derived from mechanical testing can be applied and the material response can be predicted. Using this method a prediction of the material response of the whole component can be estimated. The turbine blade is analyzed for its thermal and structural performance. The structural and thermal analysis of a gas turbine is carried out using ANSYS 15.0.

5. Transient Thermal Analysis

Engineer/analysts often perform a steady state analysis before performing a transient thermal analysis, to help establish initial conditions. A steady state analysis can be the last step of a transient thermal analysis [25].

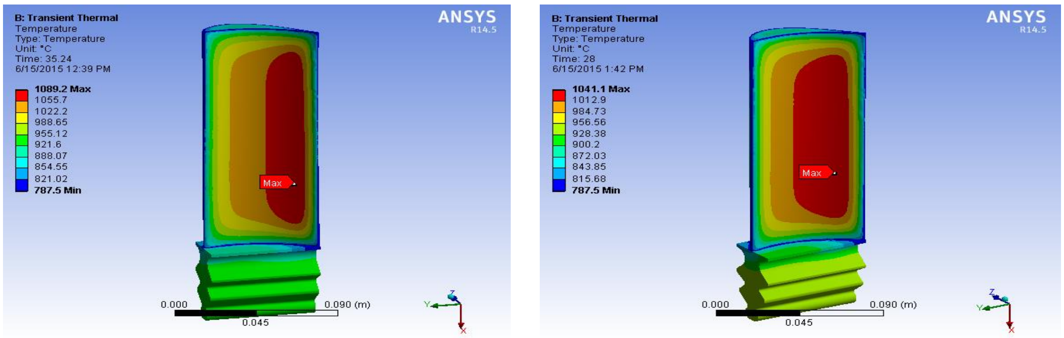

Figure 4. Transient Temperature Distribution Using Steady State Heat Transfer Coefficients at 1s on IN 792 DS and IN 754 MA

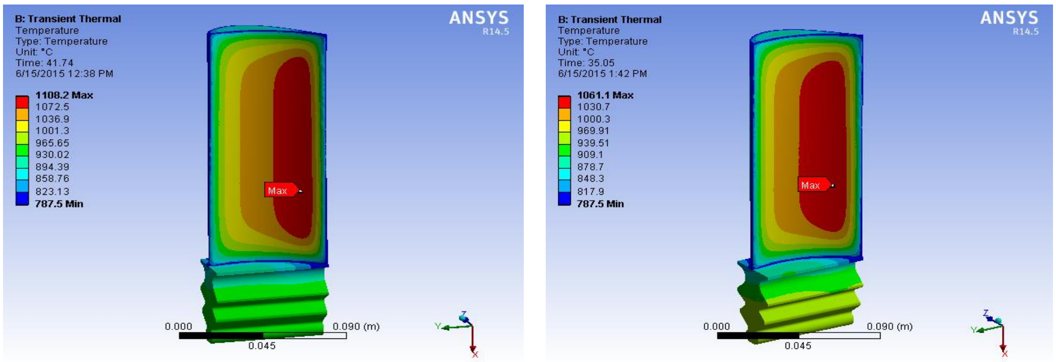

Figure 5. Transient Temperature Distribution Using Steady State Heat Transfer Coefficients at 26s on IN 792 DS and IN 754 MA

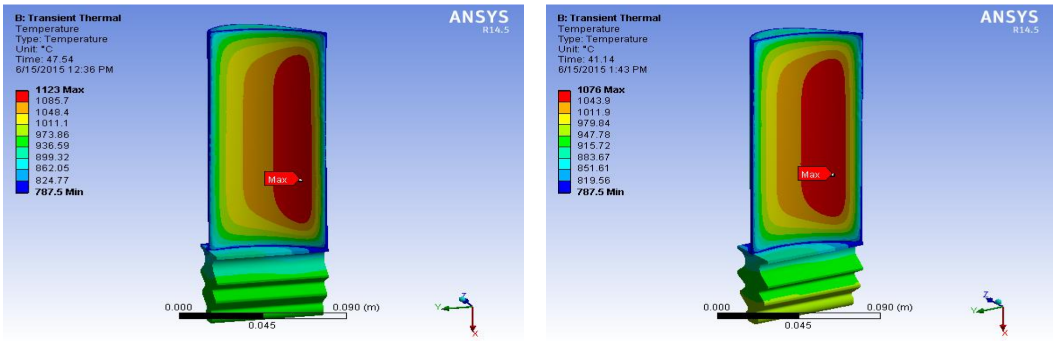

Figure 6. Transient Temperature Distribution Using Steady State Heat Transfer Coefficients at 50s on IN 792 DS and IN 754 MA

5.1. Steady State Thermal Analysis

Steady state thermal analysis is carried out before conducting transient analysis to obtain intial boundary conditions such as firing tempertaure, heat flux and film coefficient values. Thermal effects which are sighted during transient operation are shown in Figure 4, Figure 5 and Figure 6 are distributed along the blade surface at speeds 5000, 7000 and 9000 rpm respectively. Figure 7 shows the steady state thermal distribution at speed 9000 rpm of IN 792 DS and IN 754 MA.

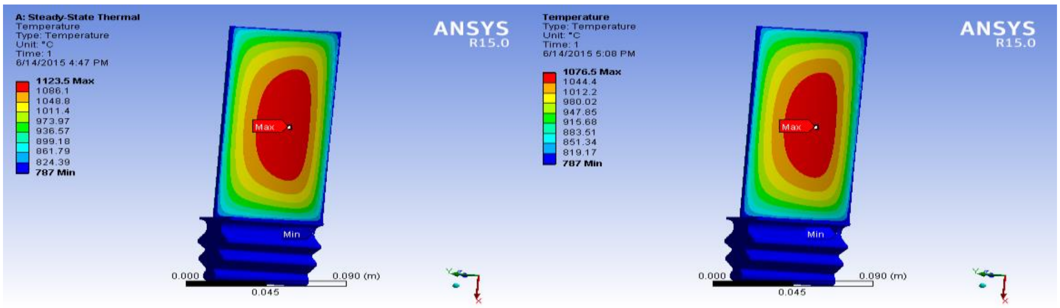

Figure 7. Steady State Thermal Distribution at Speed 9000 rpm on IN 792 DS and IN 754 MA

6. Results

6.1. Transient Thermal analysis

In this section, the results of the transient thermal analysis have been presented. For this simulation, the turbine inlet temperature is 950°C *i.e.*, from the design point of view a time of 50s is required until the stabilization of new steady state condition is reached. Time-step taken at each iteration is 0.02s. Maximum temperature distribution on superalloys IN 792 DS, IN 754 MA and IN 738 LC at various speeds with respect to time are shown in Table 3.

The temperature variation results with respect to engine parameters such as speed, turbine inlet temperature and ambient temperature. It has been observed that the temperature distribution is uniform and the maximum temperature obtained is within the melting point.

Table 3. Transient Thermal Distribution on Blade Materials with Time

Speed	IN 792 DS		IN 754 MA		IN 738 LC	
	Time (s)	Max. Temp. obtained (°C)	Time (s)	Max. Temp. obtained (°C)	Time (s)	Max. Temp. obtained (°C)
5000	35.25	1089	28.00	1041	23.74	1024
7000	41.74	1108	35.05	1061	30.34	1044
9000	47.54	1123	41.14	1076	36.64	1060

Table 4. Maximum Temperature Distribution Obtained On Turbine Blade Materials

Superalloy	Melting Temperature (°C)	Max. Temperature obtained (°C)
IN 792 DS	1450	1123
IN 754 MA	1370	1076
IN 738 LC	1300	1060

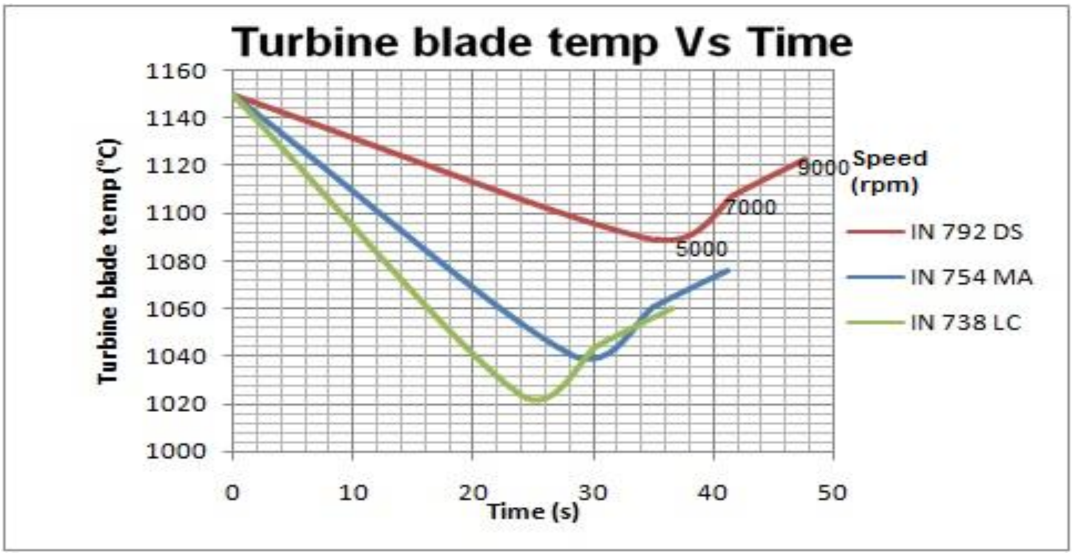

Figure 8. Temperature Distribution on Turbine Blade during Start-Up

6.2. Static Structural Analysis

Static structural analysis for turbine blades made up of IN 792 DS and IN 754 MA has been conducted. It has been observed that there is a significant effect on turbine blades at higher rotational speeds and maximum von-mises stresses are sighted on IN 754 MA.

It has been observed that IN 738 LC has minimum von-mises stresses and IN 792 DS has minimum total deformation compared to other materials which are considered for structural analysis. Table 5 shows the maximum von-mises stresses, maximum equivalent strain and total deformation at various rotational speeds for alloys IN 792 DS and IN 754 MA. Further as said, these materials are compared with IN 738 LC which shown in Table 6.

Table 5. Static Structural Analysis

SUPERALLOY	INCONEL ALLOY 792 DS			INCONEL ALLOY 754 MA		
SPEED	σ_{max} (Mpa)	ε_{max} (m)	δ_{max} (mm)	σ_{max} (Mpa)	ε_{max} (m)	δ_{max} (mm)
5000	291	0.014	1.11	276	0.0012	1.14
7000	510	0.024	2.17	526	0.0024	1.92
9000	833	0.040	3.13	860	0.0039	3.13

Table 6. Comparative Static Structural Analysis

SUPERALLOY	INCONEL ALLOY 738 LC		
SPEED	σ_{max} (Mpa)	ε_{max} (m)	δ_{max} (mm)
9000	820	0.0041	3.29

From Figure 9 shows the total deformation on blade materials with respect to turbine rotor speed (rpm). It has been observed that IN 738 LC has maximum deformation and IN 792 DS has minimum deformation at nominal rotor speeds and followed by IN 754 MA.

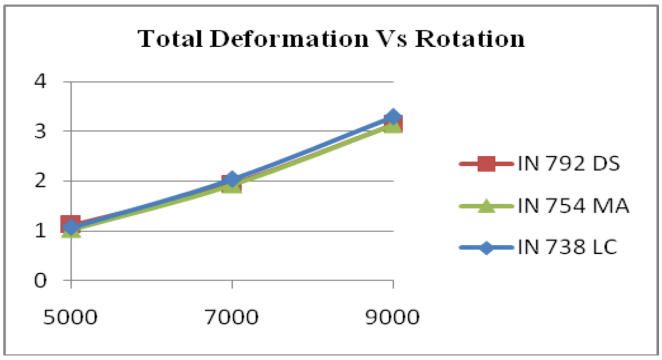

Figure 9. Total Deformation Vs Rotation

From Figure 10 shows the von-mises stresses on blade materials with respect to turbine rotor speed (rpm), considered for static structural analysis. It has been observed that IN 738 LC has minimum stresses and maximum for IN 754 MA and followed by IN 792 DS.

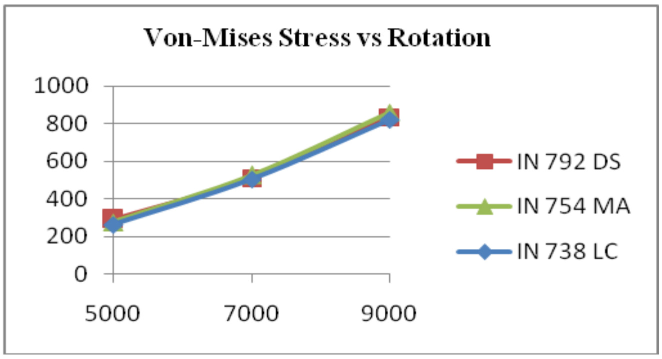

Figure 10. Von-Mises Stress Vs Rotation

From Figure 11 shows the equivalent elastic strain on blade materials with respect to turbine rotor speed (rpm), considered for static structural analysis. It has been observed that Maximum strain is located on IN 738 LC and minimum for IN 754 MA and followed by IN 792 DS.

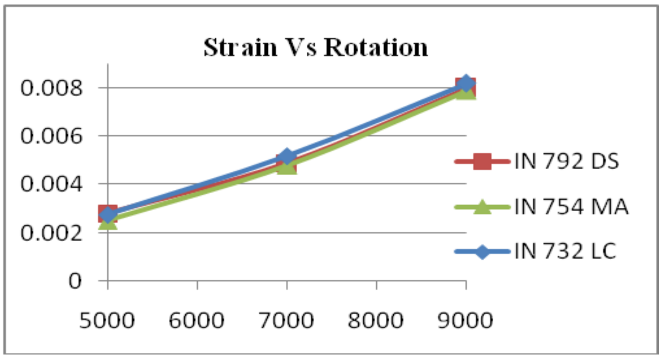

Figure 11. Equivalent Elastic Strain Vs Rotation

7. Conclusions

An attempt has been made to analyze the transient performance of the gas turbine blade. The data to make a real model of a gas turbine blade has been obtained using Co-ordinate Measuring Machine (CMM). Blade model has been generated by using CATIA V5 R21 software and been analyzed for their structural as well as thermal performance.

Structural and transient thermal analysis of the turbine blade models have been carried out using ANSYS 14.5.

The result of transient simulation for selected turbine blade model has been presented. The method was effective with three-dimensional FEMs of realistic turbine airfoils using commercial finite element applications. The main objective in solving transient thermal effects is to produce the temperature variation at start-up and shutdown of the gas turbine engine which estimates the turbine blade life.

The effects of various parameters on engine component life have been studied. ANSYS an be processed in steady state or transient mode. Steady state mode is faster to analyze, but it does not capture the engine dynamics during start-ups.

Both materials have significant effects on blade due to centrifugal loads and thermal shock. During all computations it was assumed as a rotation of nominal speed and all the boundary conditions varies as a function of time and temperature except the bulk temperature. The maximum temperature gradients on the turbine blade during all the start-up cycles were invariably registered at the center of the blade cross section. This zone corresponds to temperature gradients occurring on the pressure side. Therefore it has been observed that greater thermal stresses are sighted at transient regime.

From the results of static structural analysis, it has been observed that the stresses induced in both the materials are found to be within the limit (Yield strength). Maximum stresses are observed at the root section of the blade minimum stresses are observed in the portion of blade root.

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