Failure Analysis of Turbojet Gas Turbine Blades Used in Fighter Aircraft

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Abstract- *In the present work the first stage rotor blade of a two-stage gas turbine has been analyzed for structural, thermal using commercial software which is Finite Element Software. In the process of getting the thermal stresses, the temperature distribution in the rotor blade has been evaluated using this software the point challenging in engineering is regarding aspects of stress developed, high temperature variation in the first stage gas turbine blade of fighter aircraft. The blade examined was made up of titanium alloy. This also deals with the detection of failure of the blade at inceptive temperature, stresses and pressure. This contradiction of mechanisms of GT (Gas turbine) rotor blades due to service conditions of high temperature, stress and displacement gives overall view of boundary condition and failure criteria of turbine blade. This analysis is carried out by extracting the turbine blade profile of existing turbine blade of fighter aircraft engine by 3D scanning/modeling technique. Later on importing scanned GT blade profile into hyper mesh software to extract the refined meshes for blade for further analysis. The detailed analysis is done using commercial analysis software for the blade response of thermo-mechanical loads. As a result, thermal and mechanical issues of gas turbine blade are emphasized. The results are then mathematically examined, presented in image outputs and graphs.*

Keywords- Rotor blade; turbine; failure; analysis; aircraft engine.

I. INTRODUCTION

The main Purpose of turbine technology is to extract maximum quantity of energy for the working fluid to convert into useful work with the maximum efficiency. In the present work the first stage rotor blade of the gas turbine engines has been analyzed using ansys software for the mechanical and structural integrity. We have made analysis by the stress caused by the external force and pressure, analysis of thermal stress caused by heat. The researchers have done extensive work in the analysis of gas turbine blades. [1] A.M Kolagari et al in their papers have outlined failure analysis of gas turbine blades of nickel based alloy. [2] Andrea Gamannossi et al in their paper the progressive development in terms of gas turbine materials as well as blade cooling systems have led to continuous growth in the turbine inlet temperature and the overall pressure ratio. [3] Loveleenkumarbhagi et al have reviewed on all types failures in turbine blades and have emphasized on methodologies of failure and investigate turbine blade. [4] M.Beghini, L. Bertini et al in their paper discussed on thermo mechanical fatigue issues in the GT components and they have designed an novel rig for assessing the fatigue behavior in the trailing edge of full blade. [5] Vincenzo cuffaro et al has studied the behavior of the turbine blades to very high temperature upto 1500 ℃ varying over time, high thermal gradients, creep related phenomenon, mechanical fatigue and vibrations. [6] Sushila rani et al have done failure analysis of a first stage IN738 gas. Turbine blade tip deals with investigation of cause of failure and gas turbine blade 30MW GT having tip cracks at leading and trailing edge. [7] Tim J Crter has analyzed have common failures in GT blades discussed and illustrated. [8] SelukEkici et al have done studies on experimentally and evaluated and stated that approximately 55% of the energy rate of the fuel provide to the engine cannot be used by the engine. [9] Sabrina Giuntiniand et al have presented new procedure and aimed to predict metal temperatures in a gas turbine whole with an axis symmetry approach. [10] IKpeAniekanEssienubong et al have studied the GT blades at relatively high temperatures gases by passing through the high pressure turbine stages of turbojet engine and they have done performance of efficiency of GT which may hamper longitivity in long run particularly the turbine blades.

In the present paper the blade is analyzed for failure. The theories of failure demonstrate that when a material is subjected to one type of stress i.e; axial or bending or torsional, then it is very easy to predict when the failure is likely to occur. However, if material is subjected to a complex stress system, then it is difficult to predict the failure of the material straight away. In order to predict the failure of the material combined stresses, the following theories of failure have been formulated.

Rankine’s theory or max normal stress theory.

$$\sigma_c = \frac{1}{2}\left[(\sigma_x + \sigma_y) + \sqrt{(\sigma_x - \sigma_y)^2 + 4\tau_{xy}^{\;2}}\right]$$

Guest’s theory or max shear stress theory.

$$\tau_{max} = \frac{\tau_y}{FOS}$$

Von-misses theory or max distortion energy.

$$\left(\frac{\sigma_y}{FOS}\right)^2 = \sigma_1^{\;2} + \sigma_2^{\;2} - \sigma_1\sigma_2$$

Saint Venants theory or max principle strain.

$$\frac{\sigma_y}{n} = \sigma_1 - \gamma(\sigma_2 + \sigma_3)$$

II. METHODOLOGY

The gas turbine operates on the principle of the Brayton cycle, where compressed air is mixed with fuel and burned under constant pressure conditions. The resulting hot gases are allowed to expand through turbine to perform thrust output.

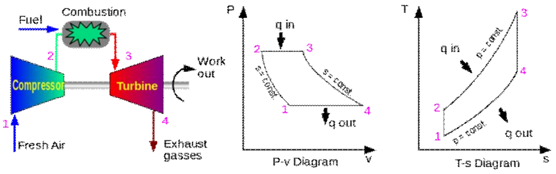


Fig 2.1 P-V and T-S Diagram of Brayton cycle

Expression for Brayton cycle thermal efficiency (η)

$$\eta_T = 1 - \frac{1}{(r_p)^{\frac{(\gamma-1)}{\gamma}}}$$

Blades of gas turbine are designed to operate in different conditions, which typically involve lower relational speeds and temperatures. Gas turbine blades are affected from various stresses, deformation, and thermal expansion more especially high rotational speeds at the elevated temperatures. The main objective of this analysis is contradiction of the failure analysis for the turbine blade by structural, thermal and modal analysis is done and validating mathematically.

Blade materials- Researchers around the world are trying to develop new material which has high strength and stability at high temperatures to meet the demands of the turbine designers. Different alloy compositions have been developed which have a good stability to withstand the thermal stresses. These alloys have been modified to give good erosion corrosion characteristics to the blades. Among the materials that have been found to be suitable for use in blades are steels, titanium alloys and nickel base alloys. All the three types of alloys which are mainly used, have varying proportions of chromium and aluminum to improve the creep strength and corrosion at high temperatures. Ending stress due to equivalent impulse load of the gases acting on the cantilever blade at a certain distance from fixing, also it must have high creep strength. Hot erosive and corrosive effects due to the high temperatures combustion products, for example, CO_2 and CO with water vapour. Varying temperatures and should have structural stability when exposed to varying temperatures.

The three types of commonly used turbine blade material and its properties is as shown in the table.

III. MATERIAL AND THEIR PROPERTIES

MATERIA / PROPERTY	**UNITS**	**TITANIUM 6AL-4V**	**INCONNEL 625**	**HASTE ALLOY X**
Density	Kg/m^3	4500	8400	8220
Young's Modulus	Pa	1.15e11	1.5e11	2e11
Poisson Ratio		0.3	0.331	0.328
Thermal conductivity	W/mK	6.7	10	28.70

IV. MODELING & ANALYSIS

In this method reverse engineering technique is used to model the blade. Since the design of the blade is complicated and involves curvature which is difficult to model, this technique is used. Here the profile of the blade is extracted using 3D scanner. The scanner which is used to extract the blade profile is stainbitchler COMET L3D scanner. The image of the scanner is as shown in figure 3.1.

Fig 3.1 Stainbitchler COMET L3D scanner

The light which falls on the object from the scanner is reflected back and the image is recorded using VISI07-ZEISS optotechnik automation software. Before scanning the blade is completely sprayed using chalk powder in order to observe complete reflection of light which falls on the object. The image which is recorded from scanning is in the form of point cloud data i.e; wrp (wrap) format. The image captured appears as shown in the figure 3.2. The software used to capture the image is Geomagic Qualify 20.

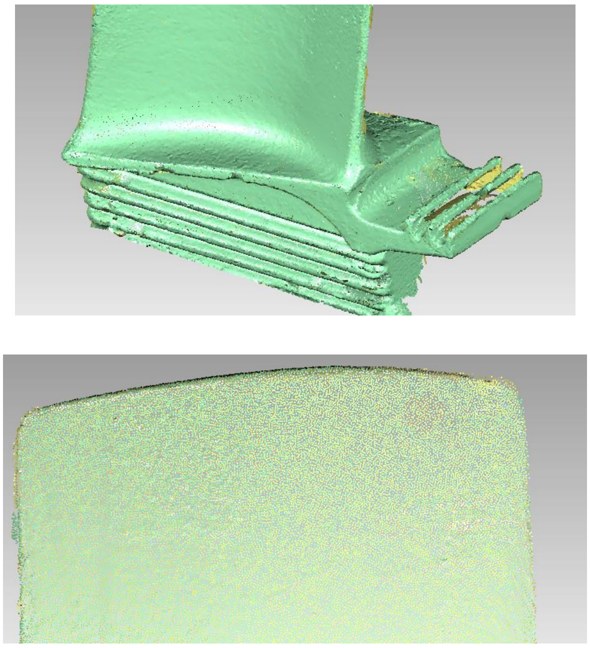


Fig 3.2 Image captured using 3D scanner point cloud data

The post processing operation is performed, at this stage the proper spacing of point is made and the unwanted points and floating edges are removed. Next all the points are wrapped and the surface appears in the form of triangular shape as shown in figure 3.3 and is converted to stl (standard triangular language) format.

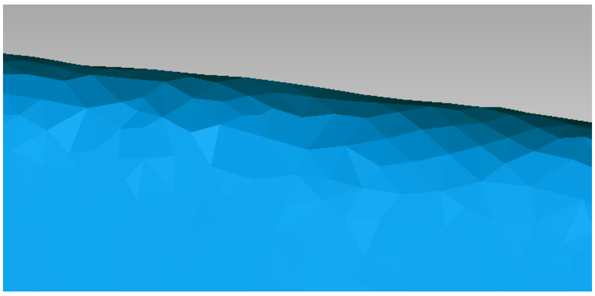


Fig 3.3 appearance of triangular shape on the surface of blade

The stl file is then arranged based on user requirement. Now the planes are created at regular intervals at a distance of 20mm and the curves are extracted in each plane and the curves which are extracted in each plane are saved asigs format. The igs format file is then imported to modeling software; the software used here is UGNX 9.0. The modeling is done using the following software and the exact profile of the blade is obtained as sown in figure 3.4

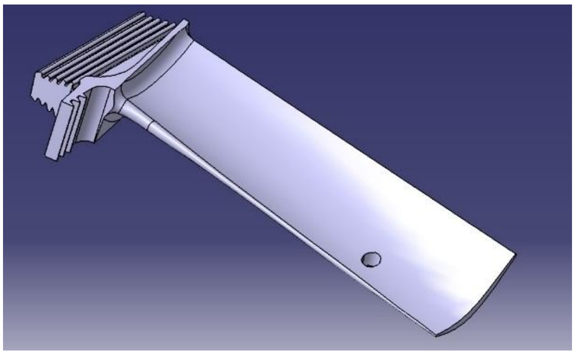


Fig 3.4 modeling of the blade using UGNX 9.0

Meshing- Mesh generation is the process of dividing a physical domain into smaller sub domains (called elements) to facilitate an approximate solution. In this process the blade is meshed into multiple elements in order to obtain the results accurately. The software used is HYPERMESH. The element type is second order tetra element. The advantage of using second order mesh is, most often we need to get results of the structural mechanics near to what they have from realistic experiments. But in practice it is always hard to get the results from simulation which nearly matches the experimental result. There are two types of tetrahedralization meshes; first order and second order mesh. The difference between the two meshes is as shown in figure 3.5.

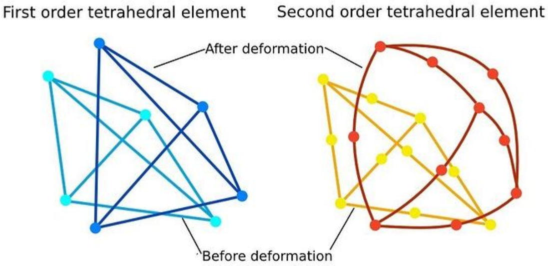


Fig 3.5 Difference between first order and second order mesh

From the above figure we can observe that second order mesh has an additional mid node due to which the deformation can be observed easily and accurately. Therefore, using second order mesh will lead to better result with less number of nodes compared to first order mesh. The type of mesh used in meshing the blade is a solid mesh. There are about 20320 elements and 50181 node contained in the mesh produced. The image of the meshed blade is as shown in figure 3.6.

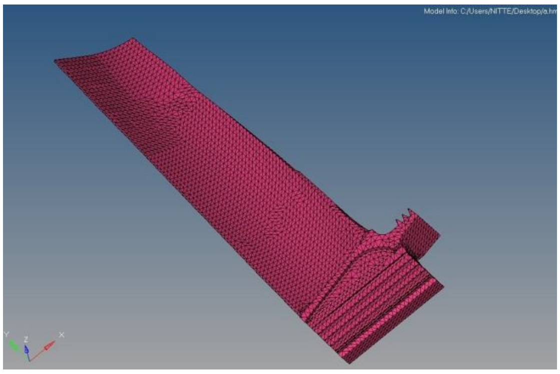


Fig 3.6 meshed blade

The blade has been masked for better understanding about the appearance of a solid second order tetra element and is as shown in figure 3.7.

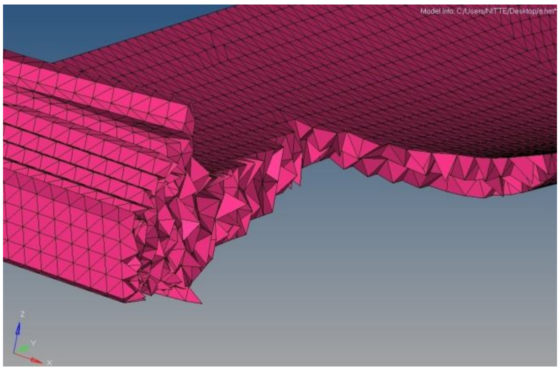


Fig 3.7 Mask view of the blade

Finite element Analysis - The FEA is a numerical computer technique used for engineering analysis. The technique is used to find a approximate solution for a partial differential equation by subdividing a large complex problem into smaller parts in order to solve computationally.

Analysis process- Preprocessing: where the finite element model is defined; choice of the type of analysis, definition of the engineering parameter of the material, mesh creation, application of loads and boundary condition. Processing: where the problem is solved using software. Post processing: Here the obtained solution is elaborated and presented to the user. Its results are analyzed mathematically.

Gas forces that act on the rotor blades generally have two components namely tangential (F_t) and axial (F_a). These forces result from the gas momentum changes and from pressure differences across the blades. These gas forces are evaluated by constructing velocity triangle at the inlet and outlet of the blades. Knowing the whirl velocity v_{w_1} & v_{w_2} at the inlet and outlet, mass flow rate $\dot{m}$ the tangential force was calculated using the following equation.

Tangential Force, $F_T = \dot{m}\,(V_{w1} + V_{w2})$

The tangential force was calculated to be 426.87$^{N/blade}$. Force of 426.87N was applied uniformly on the blade as shown in the figure.

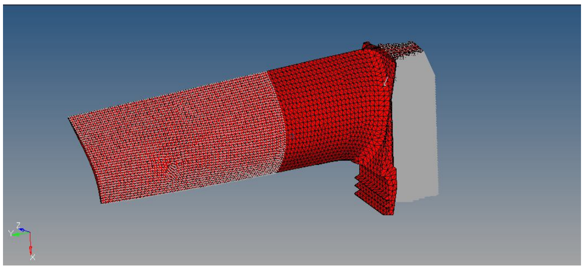


Fig 3.1 Application of load on Blade

As shown in the above figure 3.1 the region in white indicates the nodes over which the load is applied. The load is applied on 4261 number of nodes.

V. RESULTS AND DISCUSSION

A. *Structural analysis*

Blade Material: Titanium 6AL-4V

Displacement of the blade

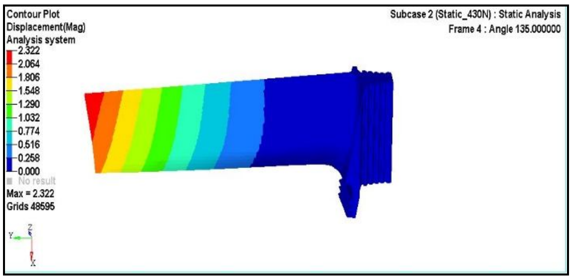


Fig 4.1 Displacement of the Titanium 6AL-4V Blade

The deformation are obtained as shown in the figure4.1; it is observed that the maximum deformation is 2.322mm

Von misses stress induced in the blade

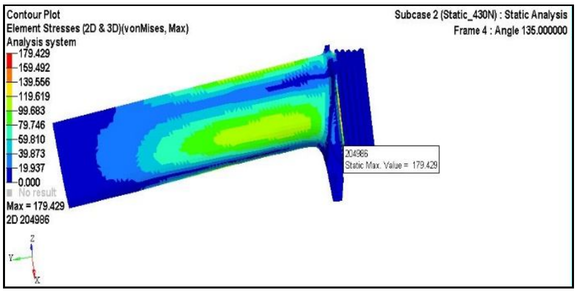


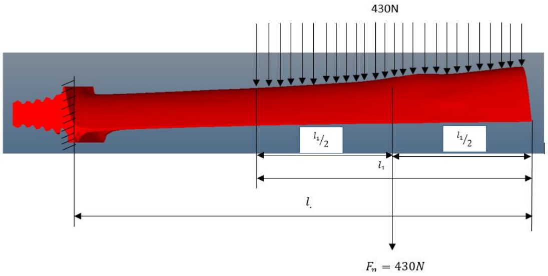
Fig 4.2 Von misse stress of Titanium 6AL-4V Blade

The vonmises stresses are obtained as shown in the figure 4.2; it is observed that the maximum vonmises stress is 179.429Mpa.

Similarly, the analysis was carried out for Inconnel 625 and Haste alloy X. The Displacement and Von misses stress for Inconnel 625 was found to be 1.782mm and 173.811Mpa. The Displacement and Von misses stress for Haste alloy X was found to be 1.336mm and 174.4Mpa respectively.

B. For the purpose of validation of numerical analyzed results analytical analysis is used

For Titanium 6AL-4V Blade



Considering the blade as a cantilever beam of length '*l*' as shown in the figure. A uniformly distributed load of 430N is applied on length 'l_1' from the tip of the blade, assuming the force close to the root is negligible.
From the classical bending moment equation, the bending moment is given as

$$M = F_n\left(l - \frac{l_1}{2}\right) \qquad (1)$$

The bending moment calculated as 37633.0625 *N-mm* and the Moment of inertia as 517.994mm^4.

The bending stress is calculated using the equation,

$$\sigma = \frac{M}{I/y} = \frac{M}{Z} \qquad (2)$$

The bending stress value is found as 199.793 N/mm^2.

Displacement of a cantilever beam with UDL is,

$$y = \frac{wl^4}{8EI} \qquad (3)$$

Displacement of cantilever beam due to force of 430N is calculated to be 2.6523 *mm*.

To find Von misses stress the equation is,

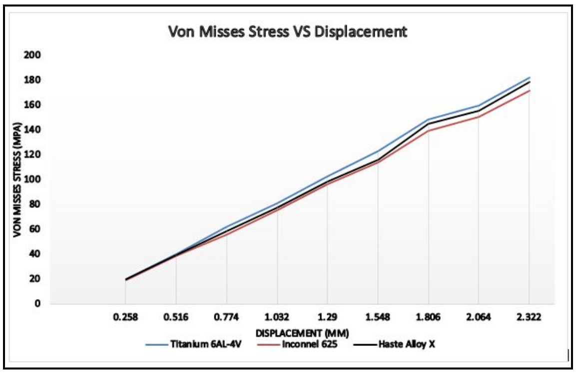
$$\sigma_v = \sqrt{\frac{1}{2}[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2]} \qquad (4)$$

The von misses stress is calculated as 184.62N/mm^2.

For Inconnel 625 Blade- The bending stress is found to be 199.793 N/mm^2.Displacement of cantilever beam due to force applied is calculated to be 2.07 *mm*. The von misses stress for different load condition is 910.375 N/mm^2 [5].

For Haste Alloy X Blade- The bending stress is found to be 199.793 N/mm^2. Displacement of cantilever beam due to force applied is calculated to be 1.5531 *mm*. The von misses stress for different load condition is 910.375 N/mm^2 [5].

VI. THE RESULTS OBTAINED ARE THEN COMPARING FOR DIFFERENT MATERIALS AND IS SHOWN IN FIGURE



The figure shows the variation of stress along the displacement for three different materials. The deviation produced by the material is minimal as each has their own significant properties. The von misses stress for titanium 6AL-4V, Inconel 625 and Haste Alloy X is found to be 179.42Mpa, 173.81Mpa and 176.22Mpa respectively. The displacement values are found to be 2.322mm, 1.782mm and 1.336mm respectively.

A. *To validate the results*

In gas turbine components such as compressor and turbine the presence of rotating blades necessitates a Small annular tip clearance between the rotor blade tip and the outer casing. This clearance, although mechanically necessary, may represent a source of loss in turbine. The gap height can be a fraction of Millimeter but can have disproportionately high influence on the stage efficiency. A large space between the blades and the outer casing results in detrimental leakages while contact between them can damage the blades. This paper refers to a turbojet engine under steady state condition. The turbine blades were analyzed for displacement for in both structural and thermal conditions. The clearance between the blade tip and casing is as shown in the figure 7.1. The clearance between the blade tip and casing was measured to be on average of 2.758mm. From the analysis results it is observed that all the three material displacement lies within the measured limit. All the three materials perform adequately.

Fig 7.1 Turbine tip clearance

VI. SUMMARY AND CONCLUSION

This paper is focused on failure analysis of HP turbine blade of a turbojet engine. The primary aim is to determine material that can withstand the service temperature of High Pressure turbine blade. Multiple simulations were performed, comparing the performance of different alloy materials i.e; Titanium 6AL-4V, Inconnel 625 and Haste Alloy X. The hange characteristics of the blade material for same loading condition leads to relative excitation of blade modes and an increased loading on overall for blade geometry. By combining different simulations as presented, the turbine blade can be analyzed to gain comprehensive insight on turbine blade function properties. The result for displacement in the blade models are analyzed and they show ever accumulating displacement on the trailing edge which in time leads to failure due to non- geometrical conformity; nevertheless, it was not expected in some parts of the blade. It was observed that in some instances the blade shows contraction especially in the leading edge. From the analysis it is observed that Inconnel 625 has better results compared to Titanium 6AL-4V. The choices of material chosen satisfy the operating condition of high pressure turbine blades in terms of high strength at relatively high temperature.

REFERENCES

[1] AM Kolagar, N Tabrizi, M Cheraghzadeh, MS Shahriari. “Failure Analysis of gas turbine first stage blade made of nickel based super ally.” Case studies in engineering failure analysis 8 (2017) 61-68.

[2] Andrea Gamannossi, Davide bertini, Dominique Adolfo, Carlo carcasci. “Analysis of the GT26 single shaft gas turbine performance and emission.” Energy procedia 126 (201709) 461-468.

[3] Sabrina giuntini, Antonio adreini, Giulio cappuccino, Bruno facchini.”Finite element transient modeling and thermo mechanical analysis.” Energy procedia 126 (201709) 746-753.

[4] Mehdi tofighi naeem, Seyed ali jazayeri, Nesa Rezamahdi,” Failure analysis of gas turbine blade.”proceeding of the 2008 IAJC-IJME international conference ISBN 978-1-60643-379-9

[5] PV Krishnakanth, G Narsa Raju, RDV Prasrd, R saisrinu.” Structural and thermal analysis of gas turbine blade by using FEM.” IJSRET Volume 2 may 2013 ISSN 2278-0882

[6] Tim J Carter.” Common failures in GT Blade.” Engineering Failure analysis 12 (2005) 237-247

[7] Vicenzo Cuffaro, Francesca cura, Raffaella sesana.” Advanced life assessment method for GT Engine components.” Procedia engineering 74 (2014) 129-134

[8] Sushila Rani, Atil K Agarwal, Vikas Rastogi.” Failure analysis of IN738 GT Blade tip cracking in a thermal power plant.” Case studies in engineering failure analysis 8 (2017) 1-10.

[9] Lukas Schwerdt, Thomas Hauptmann, Artsem Kunin, Jorg R Seume.”Aerodynamically and Structural analysis of operationally used turbine blades.” Procedia CIRP 59 (2017) 77-82.

[10] Lin Min, Yu Ling, Cai Wen-Xiang.” Experiment analysis of combustion performance in pulse jet engine.” Energy procedia 100 (2016) 248-252.

[11] P Brandao, V Infante, AM Deus.” Thermomechanical modeling of HP turbine blade of airplane GT Engine.” Procedia structural Integrity 1 (2016) 189-196.