STRUCTURAL ANALYSIS OF GAS TURBINE BLADE THROUGH COOLING HOLES USING ANSYS

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ABSTRACT

Today, Gas turbines are one of the most widely used for air craft propulsion, land based power generation and industrial applications. The temperature at which the turbine operates (firing temperature) also impacts efficiency, with higher temperature leading to higher efficiency. However, inlet temperature of a turbine is limited by the thermal conditions that can be accepted by the turbine blade metal alloy. Gas temperatures at the turbine can be 1200C to 1400C but some manufactures have boosted inlet temperature as high 1600C by engineering blade coatings and cooling systems to protect metallurgical components from thermal damage. In the present work to examine the heat transfer analysis of gas turbine with different models consisting of blade with varying number of holes (5,9&13) were analyzed to find out the optimum number of cooling holes. The Steady state structural analysis is carried out using ANSYS software with different blade materials of chromium steel and Titanium Alloy.

Key words: *Gas turbine blade, Thermal conditions, Cooling holes (5,9& 13), Temperature, ANSYS*

I. LITERATURE SURVEY

Extensive work has been reported in the literature on cooling of gas turbine blade. Narasaraju et.al.[1] have considered N155 and Inconel718 nickel chromium alloy as the blade material and performed steady state thermal and structural analysis with varying number of cooling passages. It is proved that decreased temperature of the blade will reduce power out and efficiency of plant. Hence the number of cooling holes restricted to 13. Deepanraj et.al. [2] have performed Theoretical analysis of gas turbine blade by finite element method and considered titanium-aluminum alloy as the blade material and it is concluded that blade configuration with 8 holes given as optimum blade temperature of 800°C.

II. DETAILS OF A GAS TURBINE BLADE

2.1 Materials of Turbine Blade

A Crucial limiting factor in jet engines was depends upon the performance of the materials available for the key section (combustor and turbine) of the engine. The need for better materials spurred much research in the field of alloys and resent trends in manufacturing technologies, and that results are existed from research in a long list of new materials and methods that make modern gas turbines possible.

The improvement of super composite alloys in the 1940s and produced new processing methods such as vacuum induction melting in the 1950s greatly increased the temperature capability of turbine blades. Further processing methods like hot is static pressing improved the alloys used for turbine blades and increased turbine blade performance. Modern turbine blades often use nickel-based super alloys that incorporate titanium alloy, cobalt, and rhenium.

2.2 Details of a Gas Turbine Blade

L=200 mm, l=115 mm, D=1.2 mm, N=3426 Rpm, d=1545 mm

Table 1 Mechanical Properties of Chromium steel and Titanium Alloy

Properties	Units	Chromium steel	Titanium Alloy
E	Mpa	80700	205000
ρ	Kg/cu m	7750	8190
K	W/m-k	24	25
μ	---	0.28	0.284
Cp	J/kg-k	435	586.2
Melting point	°C	1410	1344
Yield stress	Mpa	655	1067

2.3 Turbine blade Profile:

Radius of tip is found by the following relation ship

$$r_t^2 = \frac{m}{\pi.\rho.C_a\left[1-\left(\frac{r_s}{r_1}\right)^2\right]}$$

Mass flow rate m= 40 kg/sec, C_a=gas velocity at inlet =30 m/sec, r_s= shaft radius=722.5mm

$$r_t^2 = \frac{40}{\pi x 8190 x 30\left[1-\left(\frac{0.6}{722.5}\right)^2\right]}$$

$r_t = 7.19 \times 10^{-3}$ mm

Blade speed $U = \frac{\pi dN}{60}$

$= \frac{\pi x 1545 x 10^{-3} x 3426}{60}$

=277.14 m/sec.

The axial chord length is determined by the following relationship

$$\left(\frac{b}{s}\right)_{op} = \left|\frac{2}{C_{L.OP}}\cos\alpha^2\left(\tan\alpha_{in} - \tan\alpha_{ex}\right)\right|$$

For Optimal lift coefficient $C_{L.OP}$ ranges from 0.9 to 1.2 .For this bllade $C_{L.OP} = 1$

The next ratio to predict is $\frac{O}{s}$ and $\frac{s}{e}$ which is given by

$$|\alpha_{ex}| = \frac{7}{6}\left[\cos^{-1}\left(\frac{o}{s}\right) - 10^0\right] + 4\left(\frac{s}{e}\right)$$

$$|\alpha_{ex}| = 3.015$$

A good priliminary results hold up lies between $0.25 < \frac{s}{e} < 0.625$ suggested nt Wilson.

select $\frac{s}{e} = 0.50$. the trailing edge thickness is taken from $0.015c < t_{te} < 0.05c$. select 0.03c

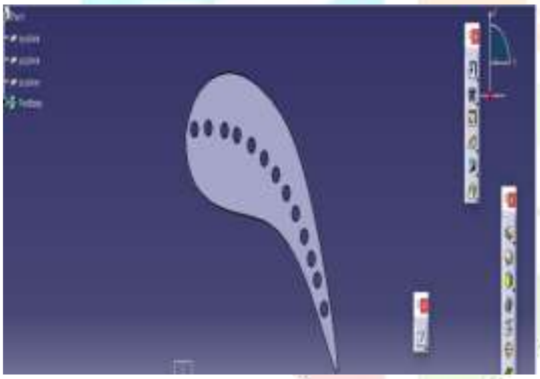
For stagger angle $\cos\lambda = \frac{b}{c}$

$= \frac{24}{28.185}$

$\lambda = 31.13^0$

III. CATIA DESIGN

CATIA offers a solution to shape design, styling, surfacing workflow and visualization to create, modify, and validate complex innovative shapes from industrial design to Class-A surfacing with the ICEM surfacing technologies. CATIA supports multiple stages of product design whether started from scratch or from 2D sketches (blueprints).



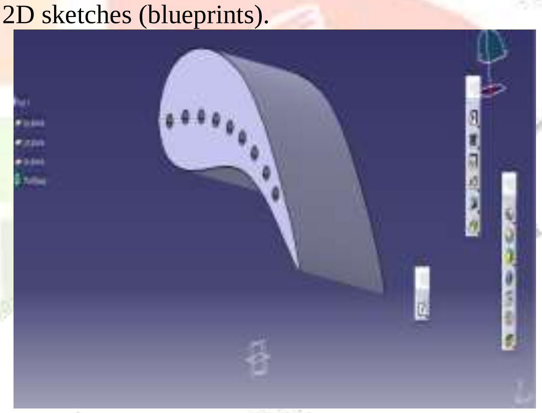


Fig: Modeling of a turbine blade with 13 holes cooling holes

Fig: Modeling of a turbine blade with 9 holes

IV. MODELING AND MESHING

4.1 Gambit

Gambit is modeling software that is capable of creating meshed geometries that can be read into FLUENT and other analysis software.

4.1.1 Coordinate Format

Since the gas turbine blade airfoil geometry is defined by sets of coordinate points, the more points defined will increase the accuracy of the model. An airfoil geometry defined by twenty points for both the top and bottom surface will result in a good definition. The list of coordinates seen in figure. were derived by scripting equations 1-6 into a Mat lab M-file, which can be found in the appendix, which then supplied the corresponding x, y, and z coordinate for each of the twenty points along the upper and lower surface of the airfoil. With the coordinates defined, they must be listed in a text document in the following format:

Fig.4.1 Proper Coordinate format for Reading Coordinates into Gambit.

4.1.2 Creating the Gas Turbine Blade Geometry

Launch Gambit. Once Gambit is open make certain the solver is set for the appropriate output, i.e. **FLUENT 5/6**, by selecting **Solver→ FLUENT 5/6**. The coordinate document must now be imported into Gambit. This is done by selecting File→ Import→ ICEM Inputs→ This will open the **ICEM import** window.

4.1.3 Create Boundary

Geometry operation→ volume command→Brick size of 0.05x0.2x0.05m size volume as a boundary of a blade, **Geometry operation→ volume command→Blend real volumes** champers left range 0.02, right range 0.01m, then it create the blade boundary .

4.1.4 Create holes on turbine blade

Geometry operation→ volume command→Cylinder size height 0.2and radius0.0003m, and select move/copy option and move mid cord of the airfoil, the turbine blade with 5 number of holes copy 4 at a distance of 0.01m in X-axis. **Geometry operation→ volume command→Subtract real volumes** Subtract blade volume to cylinder select apply. The turbine blade with 9 number of holes copy 8 at a distance of 0.005, and 13 number of holes copy 12 at a distance of 0.0035.

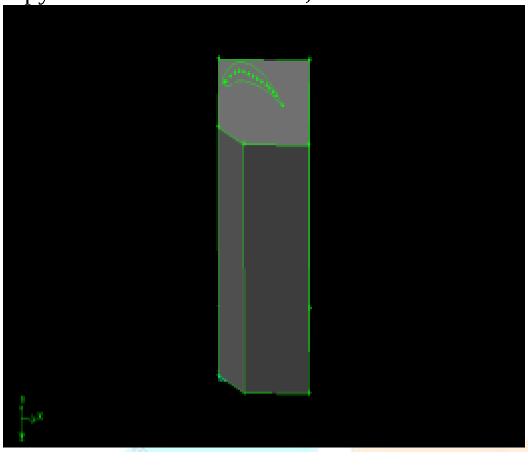


Fig: Create Boundary of Turbine Blade

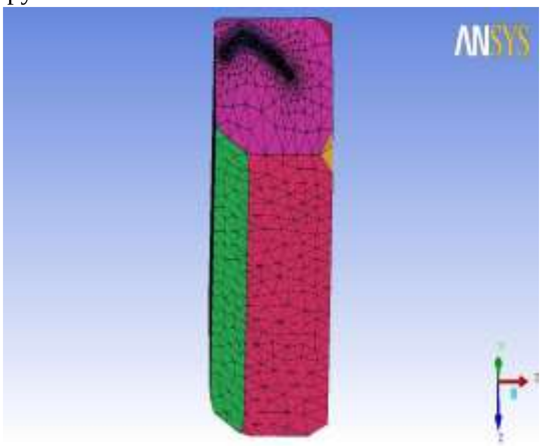


Fig: Blade mesh with 13 number of holes

V. STRUCTURAL ANALYSIS

In ANSYS the turbine blade is analysed sequentially with thermal analysis preceding structural analysis. Import the model in to ansys then define element type **Main Menu→ Preprocessor →Element Type→ Add** and at the left column mention structural solid and at the right column select the Solid 20 node 90 and Brick 8node 185. And mention the material properties of selected material. Next specify the mesh controls in order to obtain a particular mesh density. By select the **Meshing→ Mesh Tool** and mention the element edge length is 0.5, and extrudes the meshed area into meshed volume with the length of the turbine blade is 200. By apply the temperature and convection loads on surface elements, and then initialize the solution by select the **Solution→ Solve→ Current LS**. After the solution is done then select the **General post processor→ Plot results→ Counter plot→ Nodal solution** the results can be obtained.

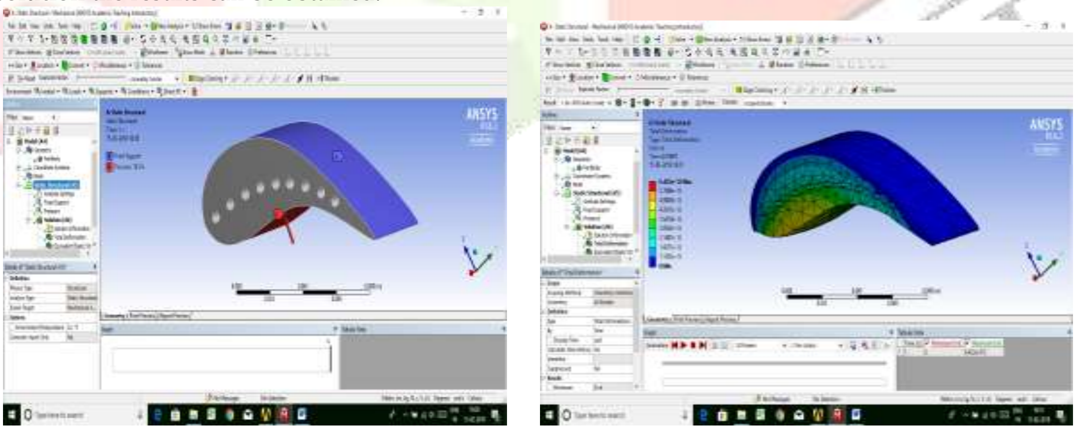


Fig: 5.14 Meshing of Turbine Blade

The structural analysis is carried out after thermal analysis. For structural analysis define the element type as Solid 20 node 90 and Brick 8node 185, and proceed the meshing as same as thermal analysis. At that point say the material properties as indicated by the chose material. By apply the pressure and displacement loads on regions and instate the arrangement by select the Solution→ Solve→ Current LS and then plot the results.

VI. RESULTS AND DISCUSSIONS

6.1 Structural Analysis of Turbine Blade

The steady state structural analysis is carried out with different blade materials of Chromium Steel and Titanium Alloy to determine the thermal flux and stresses induced in the blade.

Table2: Show the variation of Displacement, Stresses, Strains of chromium steel and Titanium Alloy with respect blade with without holes and blades with varying number of holes.

No. of holes	Material	5	9	13
Displacement(mm)	Chromium Steel	6.19 e^{-12}	6.42 e^{-12}	6.72 e^{-12}
	Titanium Alloy	5.43 e^{-12}	5.61 e^{-12}	5.85 e^{-12}

Stresses(N/mm^2)	Chromium Steel	41.678	27.918	27.1 91
	Titanium Alloy	41.178	27.189	26.256
Strain	Chromium Steel	3.43 e^{-10}	3.60 e^{-10}	5.17 e^{-10}
	Titanium Alloy	2.80 e^{-10}	3.06 e^{-10}	4.30 e^{-10}

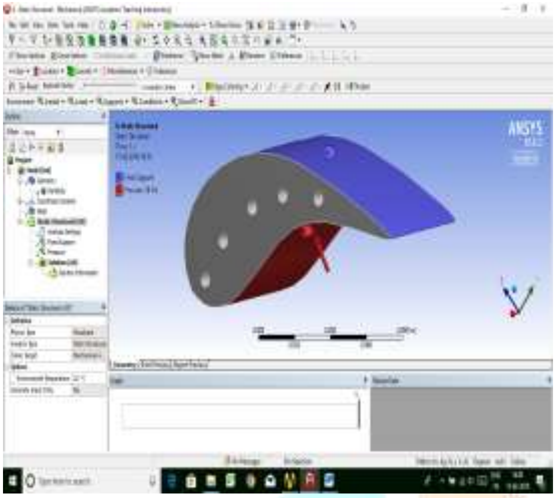


Fig (a) Chromium steel blade with 5 no of holes

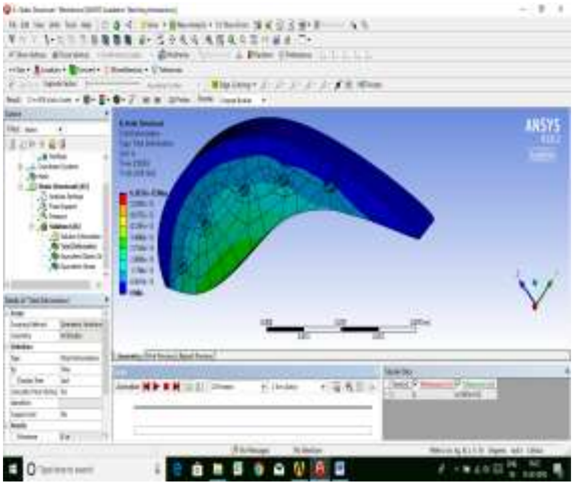


Fig (b) Displacement of blade with 5 no of holes

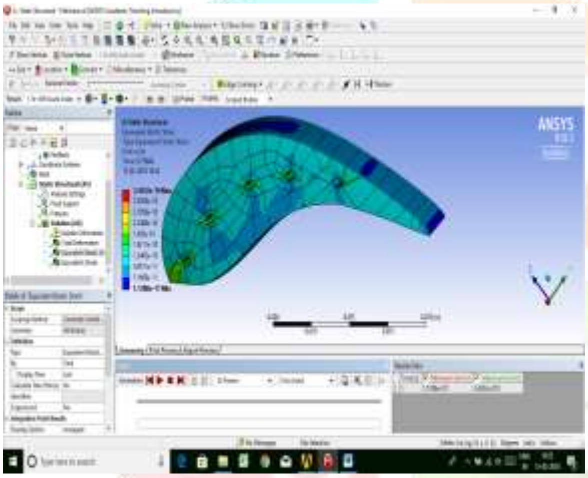


Fig (c) Strain of blade with 5 no of holes

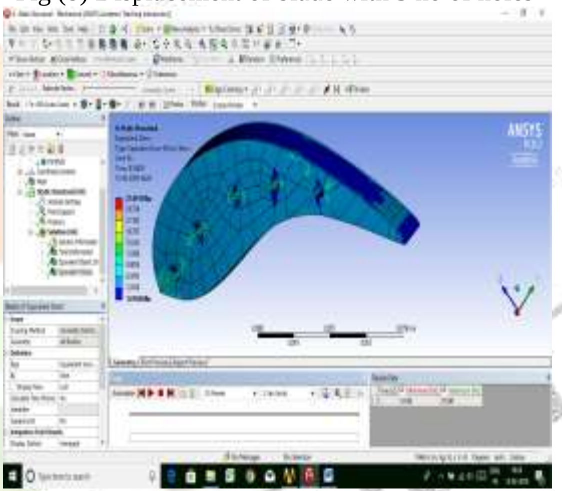


Fig (d) Stress of blade with 5 no of holes

Fig 6.1: Variation of Displacement,Stresses and Strain of Chromium Steel with respect of blade with 5 no of holes.

Figure shows variation of Displacement,Stresses and Strain of Chromium steel with respect of blade with 5 no of holes. It is observed from figure that the maximum displacement,stresses and strains of blade containing 5 no of holes is observed as 6.19 e^{-12}mm, 27.961N/mm^2 and 3.43 e^{-10}.

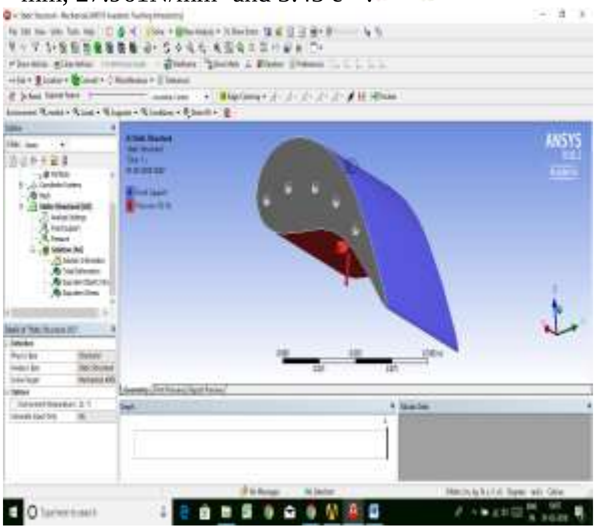


Fig (a) Titanium blade with 5 no of holes

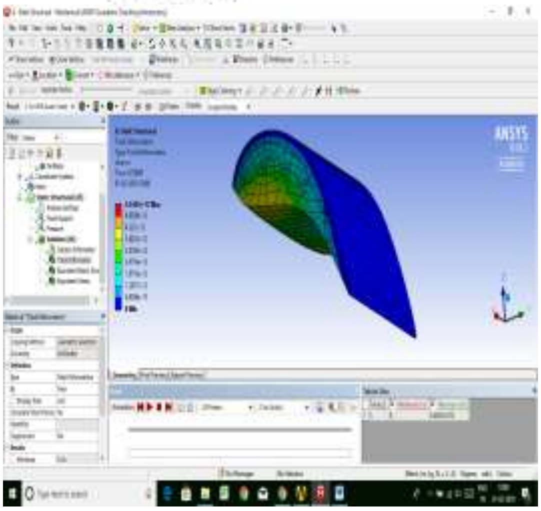
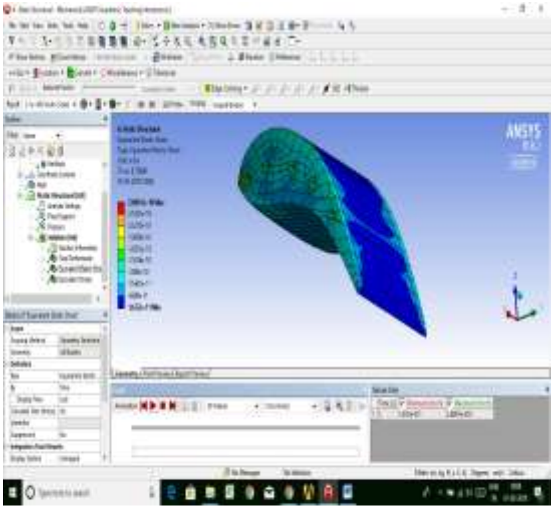


Fig (b) Displacement of blade with 5 no of holes



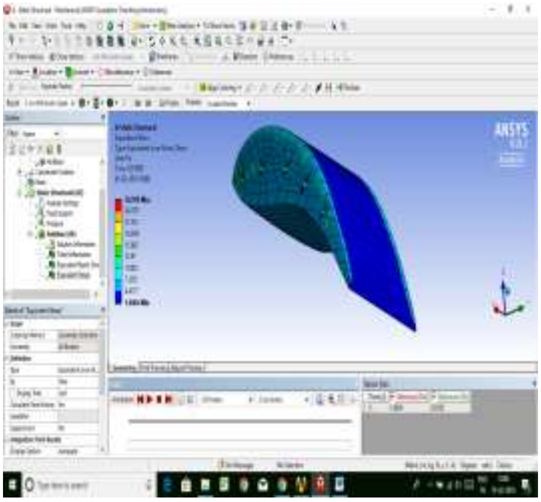
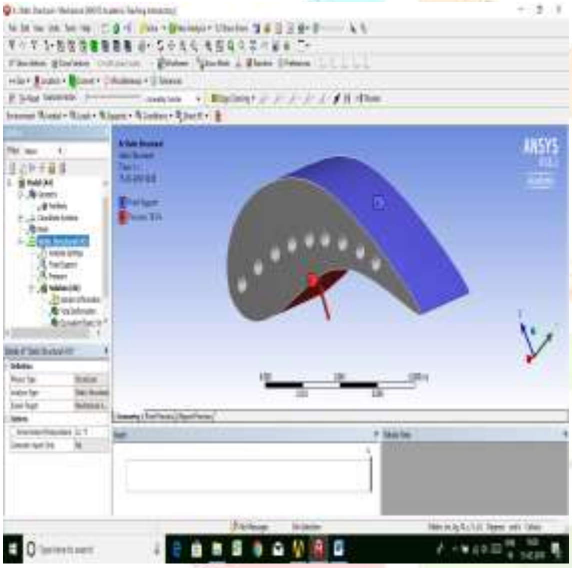


Fig (c) Strain of blade with 5 no of holes Fig (d) Stress of blade with 5 no of holes

Fig 6.2: Variation of Displacement,Stresses and Strain of Titanium Alloy with respect of blade with 5 no of holes.

Figure shows variation of Displacement,Stresses and Strain of Titanium Alloy with respect of blade with without holes and blade with 5 no of holes. It is observed from figure that the blade containing 5 no of holes is observed as 5.43e^{-12}mm, 26.956 N/mm^2 and 2.80e^{-10}.



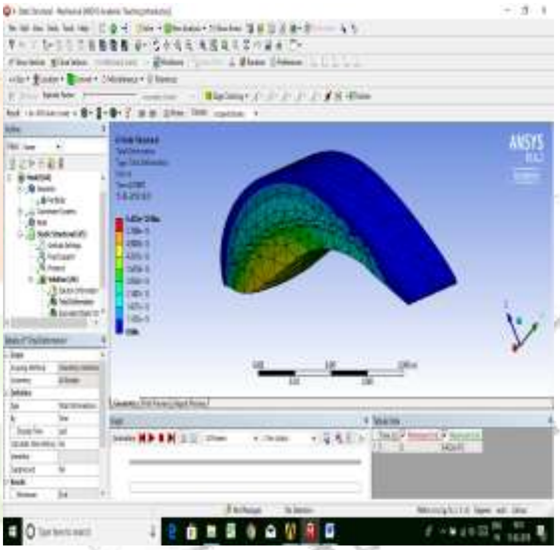
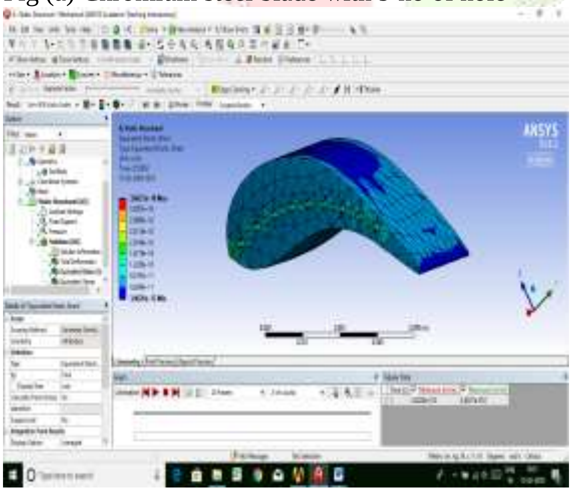


Fig (a) Chromium steel blade with 9 no of hole Fig (b) Displacement of blade with 9 no of holes



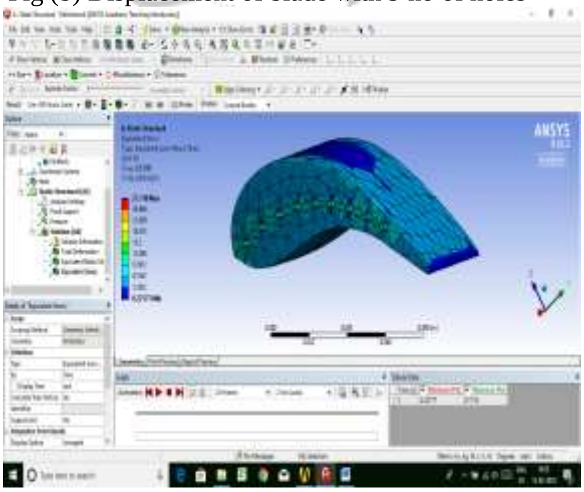


Fig (c) Strain of blade with 9 no of holes Fig (d) Stress of blade with 9 no of holes

Fig 6.3: Variation of Displacement,Stresses and Strain of Chromium steel with respect of blade with 9 no of holes.

Figure shows variation of Displacement,Stresses and Strain of Chromium steel with respect of and blade with 9 no of holes. It is observed from figure that the maximum displacement,stresses and strains of blade containing 9 no of holes is observed as 6.42 e^{-12}mm, 27.718N/mm^2 and 3.60 e^{-10}.

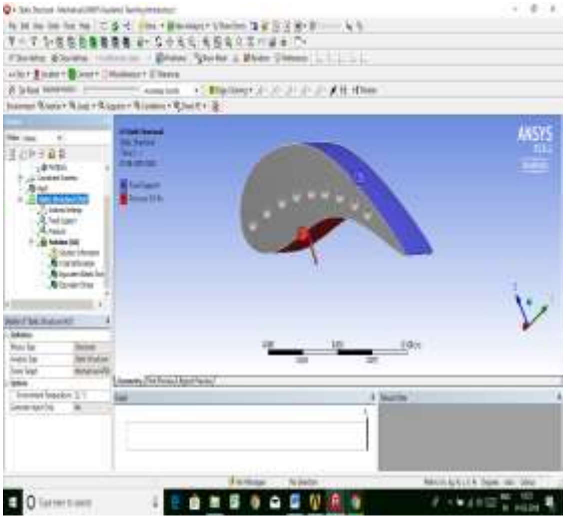


Fig (a) Titanium Alloy blade with 9 no of holes

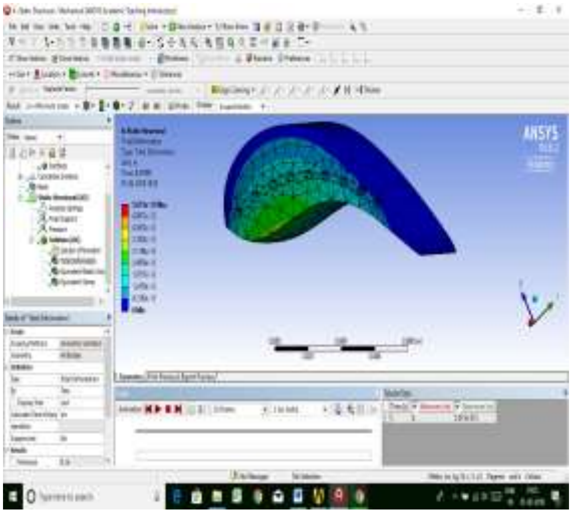


Fig (b) Displacement of blade with 9 no of holes

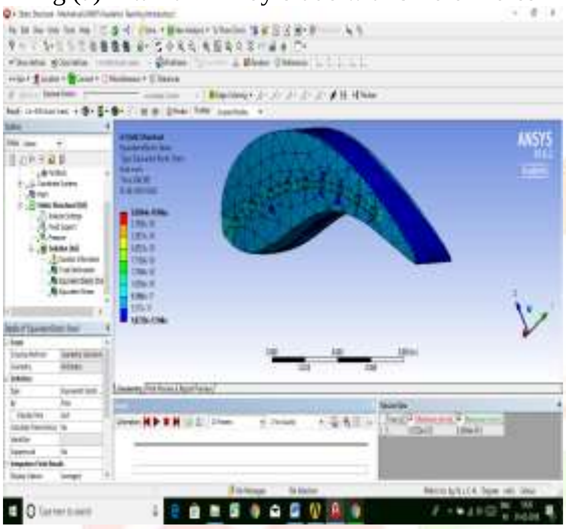


Fig (c) Strain of blade with 9 no of holes

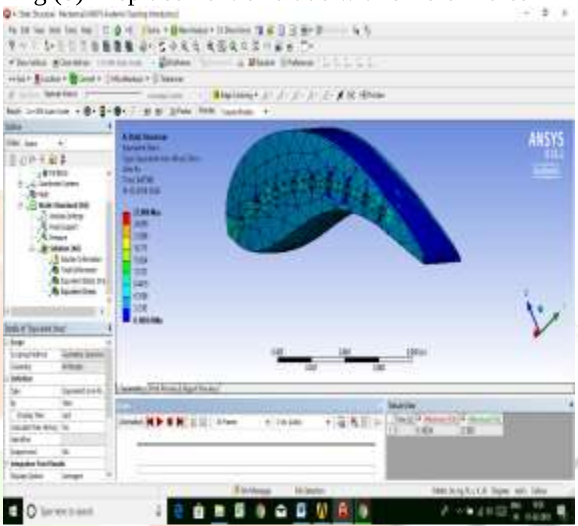


Fig (d) Stress of blade with 9 no of holes

Fig 6.4: Variation of Displacement,Stresses and Strain of Titanium Alloy with respect of blade with 9 no of holes.

Figure shows variation of Displacement,Stresses and Strain of Titanium Alloy with respect of blade with 9 no of holes. It is observed from figure that the maximum displacement,stresses and strains of blade containing 9 no of holes is observed as 5.61 e^{-12} mm , 27.989 N/mm^2 and 3.06 e^{-10}.

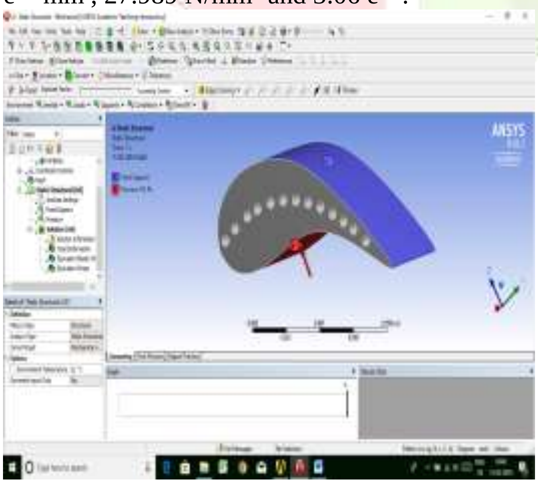


Fig (a) Chromium steel blade with 13 no of holes

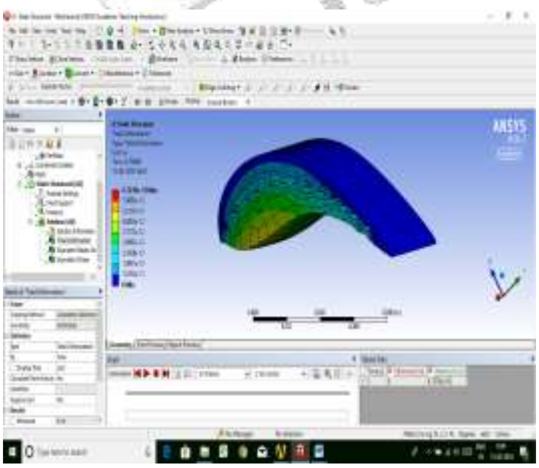
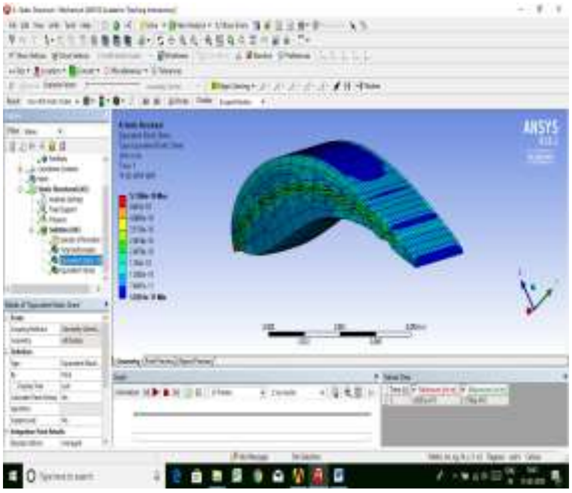


Fig (b) Displacement of blade with 13 no of holes



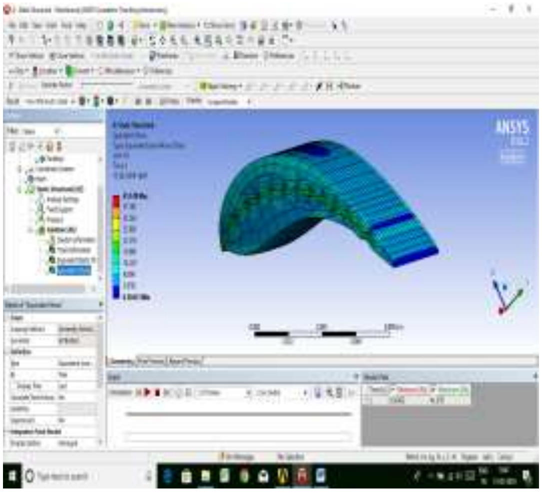
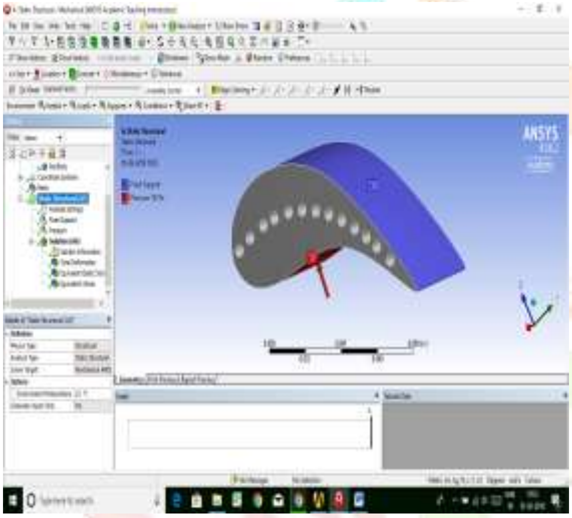


Fig (c) Strain of blade with 13 no of holes

Fig (d) Stress of blade with 13 no of holes

Fig 6.5: Variation of Displacement,Stresses and Strain of Chromium steel with respect of blade with 13 no of holes.

Figure shows variation of Displacement,Stresses and Strain of Chromium steel with respect of blade with 13 no of holes. It is observed from figure that the maximum displacement,stresses and strains of blade containing containing 13 no of holes is observed as 6.72 e^{-12}mm, 41.678N/mm^2 and 5.17e^{-10}.



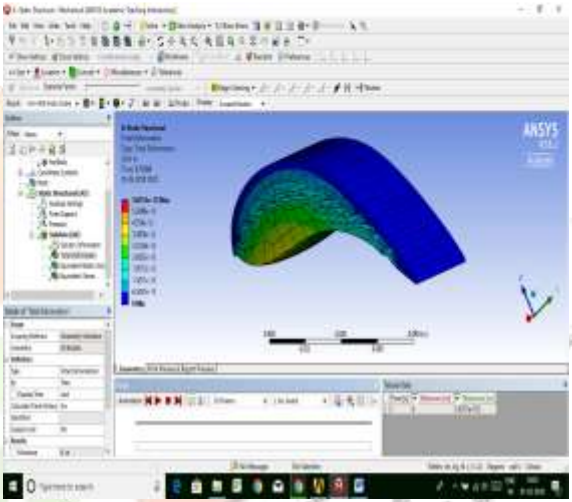
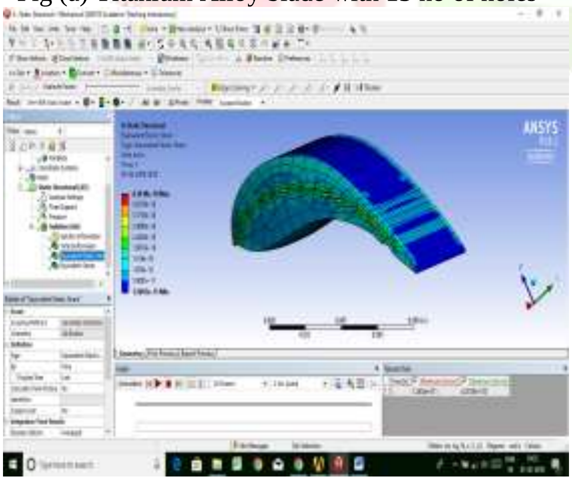


Fig (a) Titanium Alloy blade with 13 no of holes

Fig (b) Displacement of blade with 13 no of holes



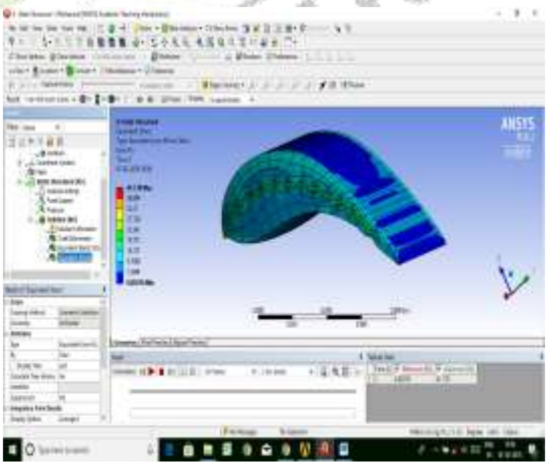


Fig (c) Strain of blade with 13 no of holes

Fig (d) Stress of blade with 13 no of holes

Fig 6.6: Variation of Displacement,Stresses and Strain of Titanium alloy with respect of blade with 13 no of holes.

Figure shows variation of Displacement,Stresses and Strain of Chromium steel with respect of blade with 13 no of holes. It is observed from figure that the maximum displacement,stresses and strains of blade containing 13 no of holes is observed as 5.85 e^{-12}mm, 41.178N/mm^2 and 4.30e^{-10}.

6.2 Theoretical calculations:

Let ε be the actual strain on the turbine blade when applied load at F.

The stress is given by the equation $\sigma = E(\varepsilon - \mu F)$

If we consider the blade, loading condition

$$\sum_1^n A_j\sigma_j=0 \Rightarrow \sum_1^n A_jE_j(\varepsilon_J-\mu_jF_j) \quad \rightarrow (6.1)$$
$$\sum_1^n A_j\sigma_jx_j=0 \Rightarrow \sum_1^n A_jE_jx_j(\varepsilon_J-\mu_jF_j) \quad \rightarrow (62)$$
$$\sum_1^n A_j\sigma_jy_j=0 \Rightarrow \sum_1^n A_jE_jy_j(\varepsilon_J-\mu_jF_j) \quad \rightarrow (6.3)$$

If it assumed the plane sections remains plane, then

$$\varepsilon_j=\varepsilon_0+px_j+qy_j \quad \rightarrow (6.4)$$

Substituting equation (4) into equation (1)

$$\varepsilon_0 \sum_1^n A_j\sigma_j+p\sum_1^n A_j\sigma_jx_j+q\sum_1^n A_j\sigma_jy_j=\sum_1^n A_jE_j\mu_jF_j \quad \rightarrow (6.5)$$

If the origin of coordinates is chosen at the centroid, so that

$$\sum_1^n A_j\sigma_jx_j=\sum_1^n A_j\sigma_jy_j=0 \quad \rightarrow (6.6)$$

Then

$$\varepsilon_0=\frac{\sum_1^n A_jE_j\mu_jF_j}{\sum_1^n A_jE_j} \quad \rightarrow (6.7)$$

Substituting from (4) into (2), we obtain

$$\varepsilon_0 \sum_1^n A_j\sigma_jx_j+p\sum_1^n A_j\sigma_jx_j^2+q\sum_1^n A_j\sigma_jx_jy_j=\sum_1^n A_jE_j\mu_jF_jx_j \rightarrow (6.8)$$

If the axes of X and Y are chosen to be principle axes

So that

$$\sum_1^n A_j\sigma_jx_jy_j=0 \rightarrow (6.9)$$

$$\text{Then} \quad p=\frac{\sum_1^n A_jE_j\mu_jF_jx_j}{\sum_1^n A_j\sigma_jx_j^2} \rightarrow (6.10)$$

$$q=\frac{\sum_1^n A_jE_j\mu_jF_jx_j}{\sum_1^n A_j\sigma_jy_j^2} \rightarrow (6.11)$$

Now the equation for the stress becomes

$$\sigma_j=E_j\left(\frac{\sum_1^n A_jE_j\mu_jF_j}{\sum_1^n A_jE_j}+\frac{\sum_1^n A_jE_j\mu_jF_jx_j}{\sum_1^n A_j\sigma_jx_j^2}+\frac{\sum_1^n A_jE_j\mu_jF_jx_j}{\sum_1^n A_j\sigma_jy_j^2}-\mu_jF_j\right) \rightarrow (6.12)$$

Stress value of Chromium steel, Consider 13 number of holes

$$\varepsilon_0=\frac{\sum_1^n A_jE_j\mu_jF_j}{\sum_1^n A_jE_j}$$

Area A $=1.72\times10^2 mm^2$, young's modulus E =80700Mpa, Poisson's ratio $\mu=0.28$, F=10 N/m^2

$$\varepsilon_0=\frac{\sum_1^{13} 1.72*10^2*80700*0.28*1\,0\text{x}10^{-3}}{\sum_1^{13} 1.72*10^2*80700}$$

$$\varepsilon_0= \quad 2.84\text{x}10^{-4}$$

From the equation $\sigma=E(\varepsilon_0-\mu F)$

$$\sigma=80700(2.84*10^{-4} \quad -0.28*10x10^{-6})$$

$$\sigma \;=22.69 \quad \text{N/mm}^2$$

Similarly for 9 number of holes

$$\sigma \;=24.06 \quad \text{N/mm}^2$$

Similarly for 5 number of holes

$$\sigma \;=30.76 \quad \text{N/mm}^2$$

Stress value of Titanium alloy, Consider 13 number of holes

Area A $=1.64\times10^2 mm^2$, young's modulus E =205000Mpa, Poisson's ratio $\mu=0.284$, F=10 N/m^2

$$\varepsilon_0=\frac{\sum_1^{13} 1.64*10^2*205000*0.284*1\,0\text{x}10^{-3}}{\sum_1^{13} 1.64*10^2*205000}$$

$$\varepsilon_0= \quad 1.84\text{x}10^{-4}$$

From the equation $\sigma=E(\varepsilon_0-\mu F)$

$$\sigma=205000(1.84*10^{-4} \quad -0.284*10x10^{-6})$$

$$\sigma \;=37.13 \quad \text{N/mm}^2$$

Similarly for 9 number of holes

$$\sigma \;=29.02 \quad \text{N/mm}^2$$

Similarly for 5 number of holes

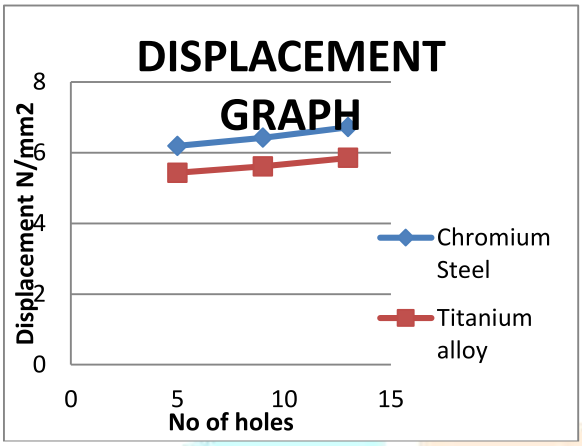
$$\sigma \;=27.106 \quad \text{N/mm}^2$$

Table 3:Comparison results

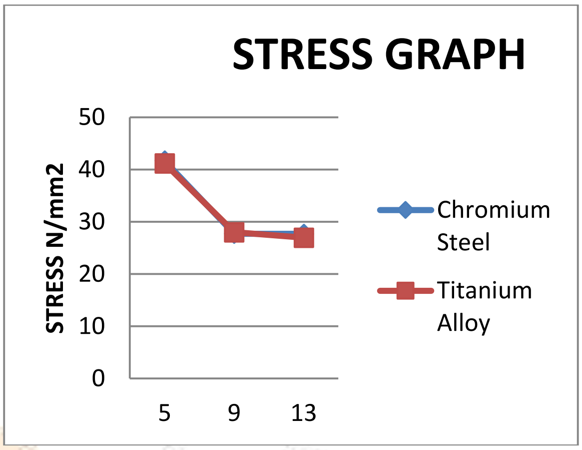
No. of holes	**Material**	**Stresses(N/mm^2)**			**Strain**		
		Analytical	**Theoretical**	**Error %**	**Analytical**	**Theoretical**	**Error %**
5	Chromium Steel	41.678	30.76	26.19	1.89x10^{-4}	3.32x10^{-4}	37.23
	Titanium Alloy	41.178	37.13	9.83	1.67x10^{-4}	2.21x10^{-4}	24.4
9	Chromium Steel	27.918	24.06	13.81	1.63x10^{-4}	2.91x10^{-4}	43.19

	Titanium Alloy	27.189	26.02	4.28	1.58x10^{-4}	2.01x10^{-4}	21.3
13	Chromium Steel	27.1 91	22.69	16.55	2.34x10^{-4}	2.84x10^{-4}	17.6
	Titanium Alloy	26.256	25.106	4.37	1.83x10^{-4}	1.98x10^{-4}	7.5

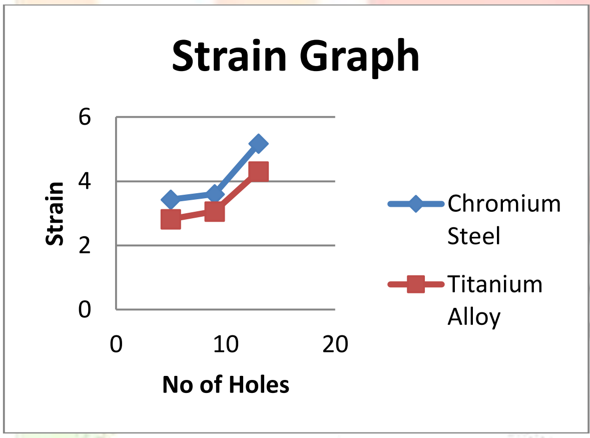
6.4 Graphs



Graph1: Maximum Displacement Vs No of Hole



Graph2: Maximum Stresses Vs No of Holes



Graph3: Maximum Strain Vs No of Holes

VII. CONCLUSIONS

The structural analysis is studied for two different materials that is Chromium steel and Titanium alloy. By observing the calculated graphs, the induced von misses stress and strain are within allowable limits. The 13 holed blade made up of titanium alloy material has better with standing capabilities like von misses stresses ,strain and deformations than comparing with the Chromium steel as discussed in the results.

Material	Stress (N/mm^2)	
	Analytical	Theoretical
Chromium Steel	27.1 91	22.69
Titanium Alloy	26.256	25.106

7.1 FUTURE SCOPE:

The internal heat transfer can be enhanced with different number of cooling passages provided at the turbine blade profile. In the present analysis radially drilled cooling holes are provided to pass the cooling air. In future demand for the more heat transfer rate of turbine blade without failure it need for the effect of rotation in ribbed channels, cooling channels with dimples and pin-fin cooling. In further rectangular and spherical shape holes also analyzed for the effect of better performance.

In the present work blade materials are used as Chromium Steel and Titanium alloy. In future it increases the turbine blade rotor inlet temperatures, and then better materials are used for higher thermal applications. Thermal barrier coatings are used for protect the external cooling of the turbine blades.

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