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Design and analysis of a high-pressure turbine blade in a jet engine using advanced materials

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ABSTRACT

In this study, the use of Inconel 625, Palladium alloy and Titanium alloy have been done in jet turbine blade. The modelling of the turbine blade was done in Solidworks 16.0 software and its simulation was done under numerical computational method using Ansys 16.0 software. The tests conducted in the software were the equivalent stress (von misses stress), equivalent strain, and total deformation. Three types of material configuration were tested and compared: using only Ni-based alloy, using Ni-based alloy with Titanium and using Ni-based alloy along with Pd-alloy at high stress zones of the blade.

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1. Introduction

Gas turbines have become an important and reliable form of power generation in the field of transportation and mobility. Gas turbines are particularly suited for aircraft propulsion because they are light and compact and have a high power to weight ratio. Gas turbine engines can be of three types which are turbojet, turbofan and turboprop type. Turbojet is a simple type of engine which produces all the thrust from the exhaust in the turbine section. In turbofan, a fan is located at the inlet of the engine which is surrounded by a cowl which enables to suck the air into the chamber. In a turboprop, a propeller is placed at the inlet in which there is no cowl around the propeller. The propeller is geared to maintain slower spin than the turbine [1]. The turbojet engine was first demonstrated by Frank Whittle in 1937 (Fig. 1).

In the jet engine, the air is sucked in and then passed to the compressor whose function is to compress the sucked air into the smallest possible optimum volume. In the compressor, the pressure is nearly raised by 30 times along with temperature rise of up to 1000 °C depending upon the number of stages. The materials should have enough strength to overcome the failures that can happen due to these extreme conditions experiencing fatigue, creep, cracking and oxidation. The materials which are well suited to withstand these conditions are the super alloys of nickel, cobalt or iron-based alloys. Along with these elements, aluminum and titanium are added to increase the strength and chromium is added to improve the corrosion resistance [2]. The compressed air from the compressor is then passed to the combustion chamber where the compressed air is mixed with the fuel injected from the injector and ignited. Here, the temperature can reach about 1800 °C so the suitable materials which can sustain in these conditions are superalloys due to their high temperature characteristics. The use of titanium or aluminum in the case of compressor is not advisable because of the absence of any moving parts in the combustion chamber, rather the addition of refractory metals is more suitable. These are the metals which have very high resistance to heat and corrosion such as tungsten, molybdenum, and niobium [2]. The combusted gases from the combustion chamber are then passed to the turbine section which consists of the high-pressure and low-pressure turbines. The turbine is connected to the compressor through a shaft which passes along the combustion chamber. The first section of the turbine is the high-pressure turbine, in which the hottest gases from the combustion chamber flow through. The turbine blade extracts as much energy possible from these high-pressure gases. The turbine blades are subjected to intense heat conditions which can cause failures due to low cycle fatigue, high cycle fatigue, creep, corrosion, etc. Following which, the usage of materials with high strength, high melting point, good oxidation/corrosion resistance and high fatigue limit is necessary. The high temperature operation of the turbine blade can also weaken its strength and performance due to which the high-

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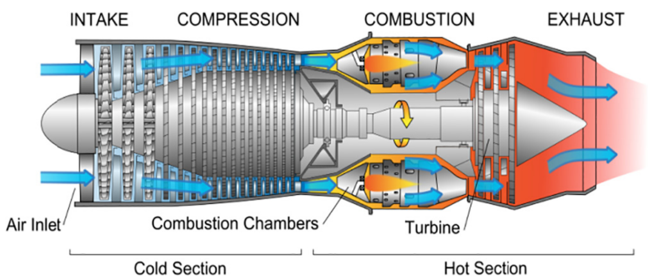


Fig. 1. Gas Turbine Jet Engine [24].

pressure turbine blades are more prone to creep and fatigue failure. Fatigue failure is one the most important factors which can cause the damage of the turbine blade, apart from secondary factors of high vibrations and resonance. The high rpm of the turbine also results in stresses induced from the generated centrifugal forces which can result in creep conditions. The material used in the high-pressure turbine is usually nickel based super alloy. According to Rolls Royce, during the past 70 years, the turbine entry temperature has increased from 1000 K for Whittle engine to higher than 1800 K for Trent 900. Considering these changes, the super alloys used for the turbine blades have also been improved in steps from wrought followed by equiaxed cast alloys to directionally solidified and single crystal alloys [3] (Fig. 2).

Considering the scope of improvement in terms of the materials used, the necessity of better suited materials led to research in the field of alloys with various manufacturing processes. This caused the researchers to discover a list of new materials and alloys for the improvement of the turbine engines [5]. For an example, in 1960 s, investing casting method was first used instead of conventional forging method to manufacture the turbine blades. It was a huge step in improving the blade life by improving the blade materials and manufacturing process. From there, directionally solidified single crystal cast alloys using the investment casting process have been used for the manufacturing of the turbine blade because of the presence of signal crystals which don't have grain boundaries eliminating the defects and impurities which occur at the boundaries [3].

1.1. Literature review

Hussain Mahamed et al. [10] studied the structural analysis of the gas turbine blade using finite element analysis. The stress and elongation of the blade was determined using different materials. The materials used were In 625, In 718, In 738, In 738 LC, MAR M246, Ni-Cr, Ti-alloy, Ti-Al, Ti-T6, U500. The result showed that the root of the blade was subjected to maximum stress for all the materials. Xu et al. [3] studied the improvement of material science and blade cooling technology. They also studied the design of blade tip to minimize the overtip leakage and also the evolution of air cooled blade technology. The evolution of blade material shows that blade materials has been changed from wrought alloys to investment casting alloys which allows them for higher temperature capability and also the resistance from environmental attack. Thermal barrier coating is used to protect the turbine blade from the corrosion. CNCs can be used as the future blade materials by overcoming various challenges. The cooling method of blade has been developed a long way from single pass convection cooling to multi pass serpentine cooling Essienubong et al. [5] studied the material selection for high pressure (hp) turbine blade of conventional turbojet engines. The motive of the paper was to find the advance materials that can withstand the high temperature of high pressure turbine of a turbo jet engine. From the study, Nickel based super alloy was selected as the suitable material for HP turbine blades as it can sustain high working temperature at a moderate cost. Krishnakanth et al. [9] studied the structural and thermal analysis of gas turbine blade. They carried out the finite element analysis of the blade. The result showed that the maximum elongations and maximum temperature were observed at the blade tip section where as the minimum elongation and minimum temperature was found to be at the root of the turbine blade. Three materials were used in the simulation which was N-155, Inconel 625 and HASTEALLOY X. Using all these materials the result showed that the maximum stress and strains were observed at the root of the root of the blade and upper surface of the blade. The result from the thermal analysis showed that the blade temperature and thermal stresses were least for Inconel 625. Surve et al. [11] used three different materials which were Aluminum alloy, Titanium alloy and magnesium alloy for the structural analysis of the blade. The results from the analysis showed that the magnesium alloy had the maximum deformation and minimum equivalent stress among the used materials where as the Titanium alloy had the minimum deformation and maximum equivalent stress. Rakesh et al. [12] designed a jet turbine rotor in CATIA and did the analysis in the Ansys workbench. Three materials were used which were aluminum 2618 alloy, titanium Ti-6Al4V alloy and nickel MAR-M-247. The results obtained were used to find the fatigue life and factor of safety of the blade. The maximum stress was found in Ti-6Al4V alloy and least in aluminum alloy including the high fatigue cycle was high in MAR-M-247 alloy. From the analysis MAR-M-247 alloy was found to exhibit better fatigue life characteristics. Ujade et al. [6] did a detailed comparative study of gas turbine blade materials and geometries using finite element analysis. Four different materials ZiCr5 Zirconium Chromite, mullet, AlSi Aluminum Silicate, Titanium Alloy were used. Two different models were developed with perforated holes number 4 and 6. The analyses of the model were done to find out the optimum number of holes. From the result, it was found that with the increase in the number of holes, the temperature of the blade was reduced. It was observed that the maximum temperature

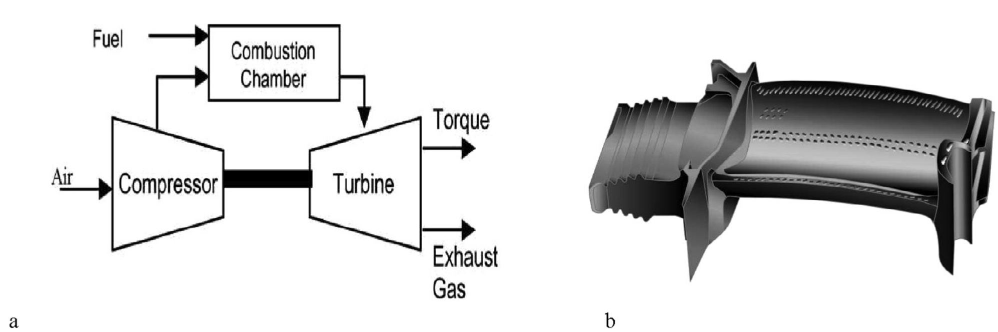


Fig. 2. (a) Flow chart of a Gas Turbine; (b) Typical Modern Gas Turbine Jet Engine Blade Showing Perforations on the Leading Edge [4].

was present at the tip of the blade and minimum temperature at the root of the blade. The temperature distribution was uniform and was linearly decreasing from the tip to the root of the blade section. The results showed that maximum elongation was found at the blade tip and minimum at the root of the blade. The elongation was minimum for the mullet taking the operating conditions same. From structural performance considerations, it was observed that mullet with 4 number of holes and from thermal performance considerations it was observed that ZiCr5 with 6 numbers of holes was best suited for the turbine blade. Theju et al. [7] studied the design and analysis of gas turbine blade. Inconel 718 and Titanium T6 were taken as the materials for the analysis of the turbine blade. The results showed that Inconel 718 had higher value of yield strength due to which less stress was induced in it as compared to Titanium T6. Kim et al. [15] studied the analysis of conjugated heat transfer, stress and failure in a gas turbine blade with circular cooling passages. The result showed the highest heat transfer coefficients occurred at the stagnation point of the leading edge where as the lowest heat transfer coefficient occurred at the trailing edge. It was also observed that the heat transfer was higher at the pressure side as compared to the suction side. The maximum stress appeared at the external surfaces of the blade at the root section. Umamaheswararao et al. [18] studied the Design and analysis of gas turbine blade with three different materials through a finite element method. Three different materials i.e. mild steel, Inconel 718 and N 188 were used for the analysis of the blade. Two different designs of models with fir tree model blade root and I section model blade root were taken. The results showed that the Von mises stress of N 188 was found to be greatest as compared to the other materials. The stress was maximum for the fir tree model blade root compared to the I section model blade root. The stress was minimum for Inconel 718 among the used materials. de Oliveira Vale et al. [19] studied methods for structural integrity analysis of gas turbine blades. The geometry modeled had a fir-tree fixing root. The analysis of the blade was conducted in Ansys 13.0 software. The study showed a great value by calculating the clearance between the teeth of the blade and the disk for thermal analysis. Nagesh et al. [16] studied the structural analysis of gas turbine blades using different materials. The aim of the experiment was to study the performance of the turbine blade using Inconel 718 and ceramics as the corresponding blade material and compare the results. The model was designed in CATIA software and the same was analyzed in ANSYS software. From the result it was concluded that Inconel 718 has a higher tendency to resist the load as compared to ceramics. Harshavardhan Reddy et al. [13] studied the effect of temperature and also of structural analysis on a gas turbine blade. The results showed that temperature has a major effect on the performance of the blade. Maximum elongation was found to be at the tip of the blade and the minimum elongation was found to be at the root of the blade. Similarly, the maximum stresses were observed at the blade root and the minimum stresses were observed at the tip of the turbine blade. N155, Inconel 625 & HASTEALLOY were used for the analysis of the turbine blade in Ansys software. The result showed that the thermal stress and blade temperature were found to be minimum for Inconel 615 and had better thermal properties. Ranjan Kumar et al. [8] studied the static structural and modal analysis of gas turbine blade. The turbine blade selected had a NACA6409 profile and the same was modeled in solidworks software and the simulation was carried out in ANSYS software. Prudhvi Raj et al. [17] studied the stress analysis of gas turbine multi stage rotor assembly. AISI-4130 super alloy steel, Hast alloy c-271 and INCONEL alloy-718 were used for the analysis of the turbine blade. The modeling was done in pro engineering software and the analysis of the same was done in Ansys software. The static, thermal and couple of both analyses was conducted for turbine rotor assembly and single blade. The results showed that the Inconel alloy 718 gave the maximum life due to its better structural properties. Abdulhussein et al. [14] studied the design and analysis of gas turbine rotor blade using finite element method. The aim of the experiment was to study the structural and thermal analysis of first stage rotor blade and a two-stage gas turbine blade. Titanium alloy, stainless steel alloy and Aluminum2024 alloy are the materials selected for the analysis of the turbine blade. The blade was modeled in 3D-Solid Brick element and the analysis of the same was analyzed in Ansys 12 software. The finite element was conducted using a eight nodded brick element. The result showed a significant effect of temperature on the overall stress of the turbine blade. There was a liner decrease of temperature from the tip of the blade to the root of the blade section. The result of the analysis showed that fundamental frequency of the Titanium alloy (Table 1).

1.2. Design of the turbine blade in solidworks 16.0

A generic CAD model of the turbine blade was made in Solidoworks 16.0 software. The design of the model is shown in the Fig. 3(a). The model from the solidworks was imported in Ansys. The model was divided into 3 bodies 1, 2, and 3 in SpaceClaim as shown in Fig. 3(b). The division of the model into 3 bodies was done to use different materials in these three different sections of the blade.

The design model of the turbine blade was imported in the Ansys 16.0 software. The meshing of the model is shown in Fig. 3 (c).

1.3. Finite element analysis

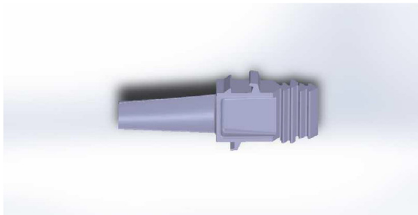
The stress analysis of a gas turbine blade is a very complicated process. Finite Element Method is an analytical method or numerical simulation method to calculate the solutions. In Finite element analysis, the body or solid is modeled and is hypothetically subdivided into an assembly of small parts called elements finite elements. Here, the finite elements mean that the geometry is divided into a finite set of small elements. The elements are connected to one another and meet at a point called joint.[20]. Thus, FEA has become a very powerful tool for the analysis of complex geometries in engineering.

1.4. Finite element analysis for turbine blade

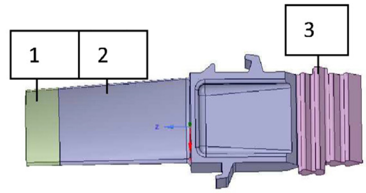
Finite element analysis was used for the determination of stress, strain and deformation of the turbine blade using different materials under same operating conditions. The turbine blade was divided into finite small elements which are interconnected with one another at joints which are known as nodes. This phenomenon of dividing the body into finite element sets is known as meshing. The meshed model of the turbine blade is shown in Fig. 3(c). A fine mesh with minimum edge length of 0.1 mm and minimum element size of 2 mm was used. The small element size was used to predict the accurate results with least possible error from the analysis. The total number of elements were found to be 647,897 and the total number of nodes was found to be

Table 1
Mechanical properties of the materials.

Properties	Inconel 625	Pd alloy	Titanium alloy
Density	8.44 g/cc	12.02 g/cc	4.7 g/cc
Ultimate Tensile Strength	880 MPa	360 MPa	600 MPa
Poisson's ratio	0.310	0.39	0.33
Modulus of elasticity	103 GPa	117 GPa	110 GPa
Tensile Strength	460 MPa	135 MPa	500 MPa

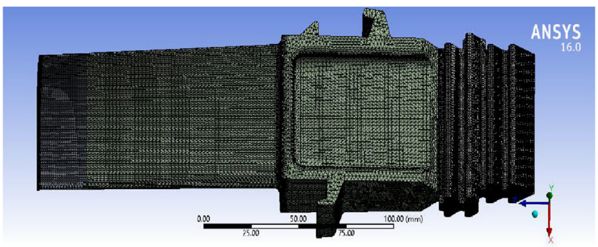


a



b

Fig. 3. (a) Model of the Turbine blade; (b) Divided sections of the bodies.



c

Fig. 3. (c) Meshed Model of Turbine Blade.

1,003,881 in the meshed model of the blade. In the analysis, the blade root section was fixed while load was applied at the tip section of the blade such that the blade acts as a cantilever and the required results were found from these boundary conditions.

2. Result

The structural finite element analysis of the turbine blade was performed using ANSYS 16.0 software. The materials selected were Inconel 625, Inconel 625 with Palladium alloy at the high stress zones and Inconel 625 with Titanium alloy at the high stress zones. The high stress zones are the regions in the blade in which the chances of failure are high [22]. The operating conditions for all the three analysis were kept same. The turbine blade is considered as a cantilever which is fixed from one end and load is applied on the face

2.1. Inconel 625

Figs. 4a–c.

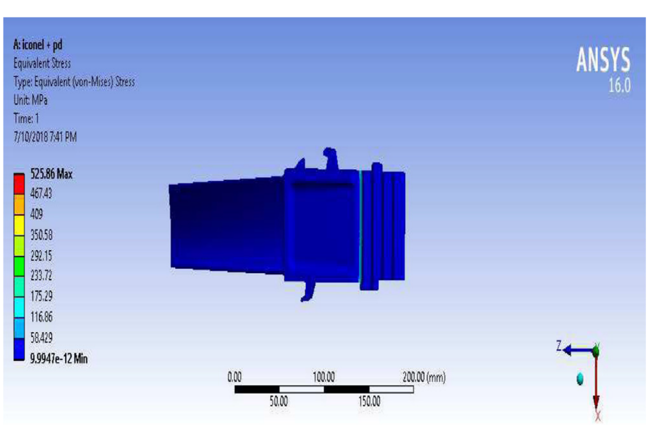


Fig. 4a. Equivalent Elastic stress Maximum value = 525.86 MPa.

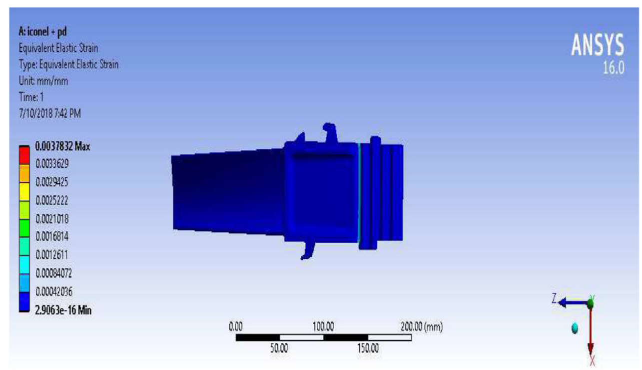


Fig. 4b. Equivalent Elastic Strain Maximum value = 0.00378.

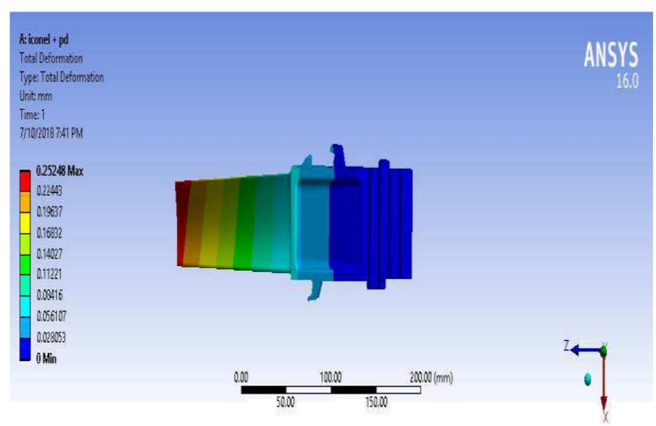


Fig. 4c. Total Deformation Maximum value = 0.25248 mm.

2.2. Inconel 625 with Palladium alloy

Figs. 5a–c.

2.3. Inconel 625 with Titanium alloy

Figs. 6a–c; Table 2.

2.4. Columns

The values of the Equivalent Stress (Von mises stress), Equivalent Strain (von mises strain) and Total Deformation of the materials are plotted as a column. This helps in clear visualization of the maximum values of the parameters. In the abscissa of the column, the materials (Inconel 625, Inconel 625 with Palladium alloy and

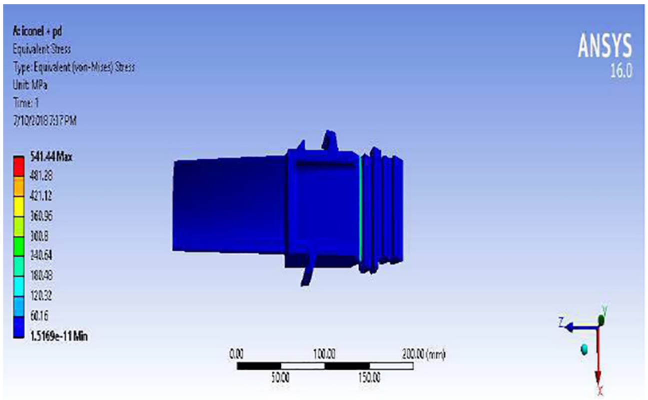


Fig. 5a. Equivalent Elastic Stress: Maximum value = 541.44 MPa.

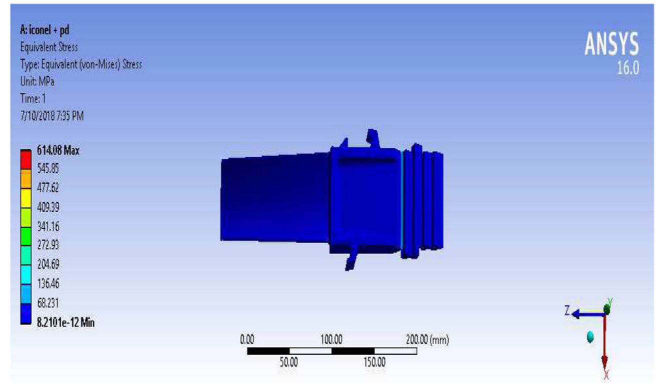


Fig. 6a. Equivalent Elastic Stress: Maximum value = 641.08 MPa.

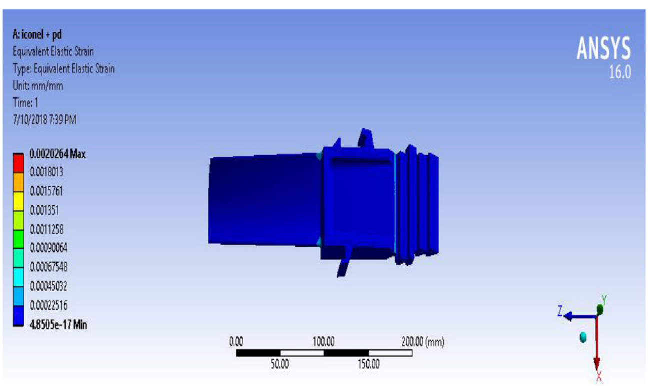


Fig. 5b. Equivalent Elastic Strain Maximum value = 0.0020.

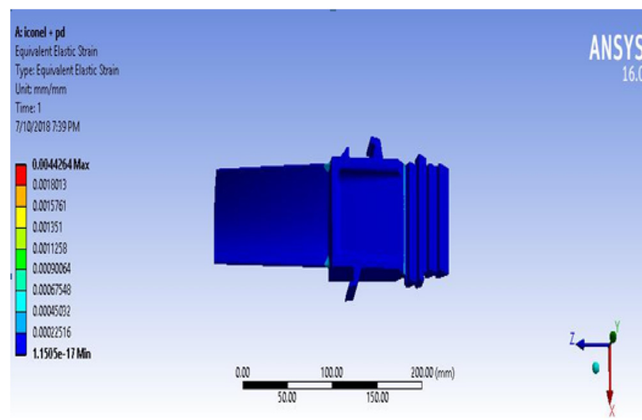


Fig. 6b. Equivalent Elastic Strain: Maximum value = 0.0044.

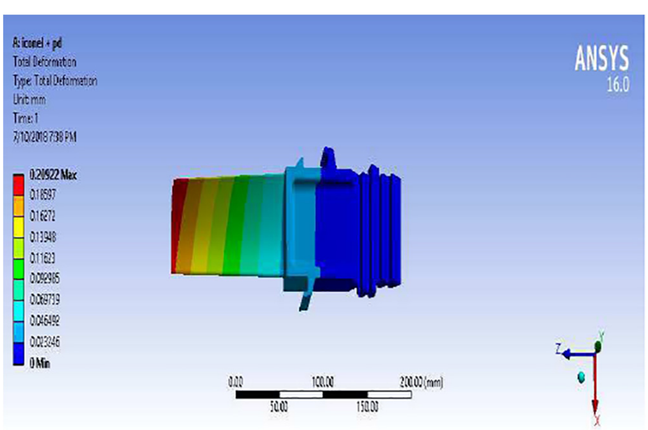


Fig. 5c. Total Deformation: Maximum value = 0.209 mm.

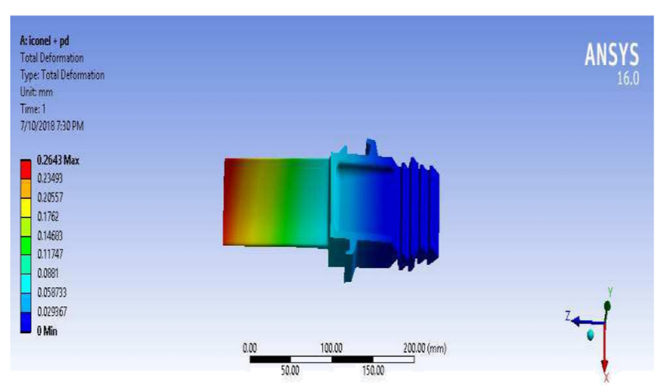
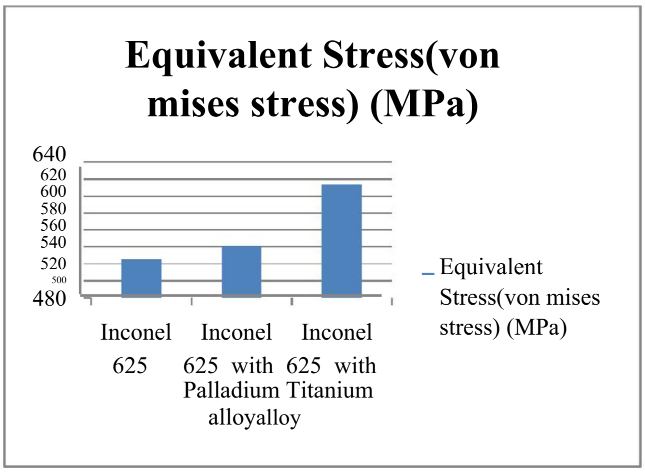


Fig. 6c. Total Deformation: Maximum value = 0.2643 mm.

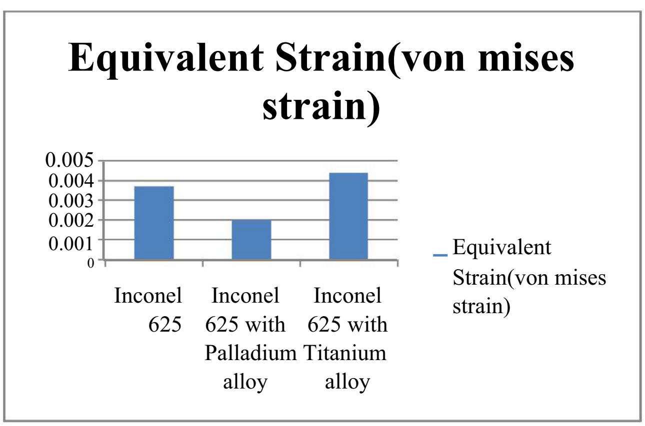
Table 2
Results comparison.

Material	Equivalent Stress (von mises stress) (MPa)	Equivalent strain (von mises strain)	Total deformation (mm)
Inconel 625	525.86	0.0037	0.2524
Inconel 625 with Palladium alloy	541.44	0.002	0.209
Inconel 625 with Titanium alloy	614.08	0.0044	0.2643

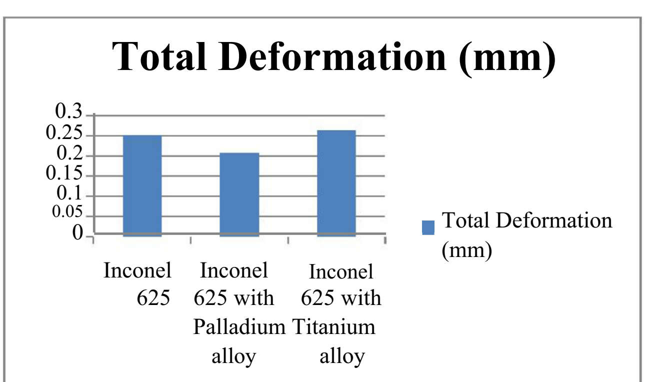
Inconel 625 with Titanium alloy) and in the ordinate of the column, the results which are equivalent stress, equivalent strain and total deformation are plotted respectively in the columns 1, 2 and 3.



Column 1



Column 2



Column 3

3. Discussion

The gas existing from the combustion chamber has a temperature of about 1700°C [5]. The melting temperature of Palladium alloy and Nickel alloy is less than 1700 and they are exposed to hundreds of degrees higher than their melting temperature, so a cooling arrangement has to be used. The cooling of the turbine blade is mainly done by two methods: designing the turbine is such a way that an internal passage is made through the blade to pass cool air or water trough it. This type of cooling is called as convection cooling in which the cool air and hot metal are in contact with each other and carries away the heat from the hot blade. For the effective cooling of the turbine blades the flow speed of the cooling air is increased, also the number of holes can be increased. The holes used are of oval shape rather than the circular shaper as the oval shaped hole has higher circumference due to which the contact area between the cooling air and blade is increased (Fig. 7).

Another method of preserving the turbine blade from the high temperature is coating a low conductivity ceramic in the outer surface of the turbine blade. The protective ceramic generally used is the stabilized zirconium dioxide-based ceramic which helps in reducing the thermal damage and oxidation. As the high temperature subjection is reduced, this helps in reducing the creep failure of the blade. The creep failure of the blade is also reduced by the directional solidification of the blade in which the grain boundaries are aligned only in one direction and by using single crystals in which there is no presence of grain boundaries. Due to the presence of grain boundaries imperfections are present in the material such as tilt boundaries and twin boundaries. Hence by using a single crystal structure, these defects are eliminated. Some other techniques to increase the blade life include preventing corrosion. One of the main reasons of corrosion is the entering of undesired particles into the turbine blade. Due to the presence of carbide, cracks can originate in the blade and the propagation of which can lead to fracture. When the corrosion is present at high temperatures, it is called hot corrosion and can damage the protective layer on the surface of the blade. Some agents that are easy to cause corrosion are NaCl, Na2So4 as Sulfur is present in most of the fuels [21]. The first stage of the gas turbine is the high-pressure gas turbine which experiences the highest temperature. So, to prevent overheating of the components and to maximize the blade life, cooling is done in the blades as it would limit the thermal stresses which are produced due to the high temperature. Film cooling is used

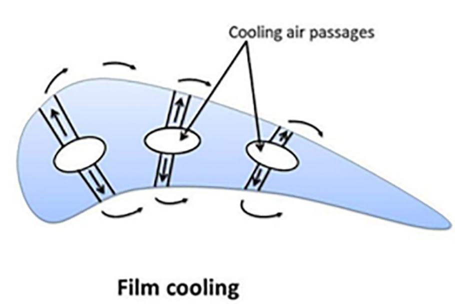


Fig.7. Film cooling in a turbine blade [23].

in most of the gas turbines which works by injecting cool air through a hole in the blade. The cool air makes a film over the hot blade skin.

4. Conclusions

The finite element structural analysis of the jet turbine blade with three different material compositions i.e. Nickel alloy Inconel 625, Inconel 625 with Palladium alloy at the high stress zone and Inconel 625 with Titanium alloy at the high stress zone was done. Three solutions which are equivalent stress, equivalent strain and the total deformation were calculated. From the analysis is was observed that

- The equivalent stress of the Inconel 625 was found to be the minimum where as the Inconel 625 with Titanium was found to be the maximum
- The equivalent strain was minimum for Inconel 625 with Palladium alloy where as it was maximum for Inconel 625 with Titanium alloy
- The total deformation was minimum for Inconel 625 with Palladium alloy and maximum for Inconel 625 with Titanium alloy

Thus, from the observed results, the use of Inconel 625 with Palladium alloy is the most suitable among the three compositions. From this study, it can be concluded that the mechanical failure of turbine blades is very prominent in gas turbines. To avoid failures, selection of the material of the blade is a very important step. The material chosen should be such that, it should withstand both the mechanical as well as thermal stresses which are produced during the operation of the turbine.

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