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Mechanical Characterization of Nickel Alloys on Turbine Blades

Animesh Nanaware [1], Shivam Pawar [2], M. Ramachandran [3]
MPSTME, SVKM's NMIMS, Shirpur, Dhule, Maharashtra, India.

animesh.nanaware.75@gmail.com[1], shivampawar900@gmail.com[2], *sweetestchandran@gmail.com*[3]

Abstract

In a Gas Turbine Engine, Turbine and Combustion Chamber are the areas having complicated problems. In Turbine section, since the gas coming out of the combustion chamber is at a high temperature and high velocity, it affects the turbine blades heavily. So the ultimate aim of this project work is to analyse a Gas Turbine Engine Turbine blade with different type of alloys for high strength against the temperature effect and other stress effects. In this project I've picked up five different & decent Ni based, high temperature withstanding alloys specially designed for aero field. Turbine blade made of those alloys is undergone flow and structural analysis by using ANSYS software package at different temperature levels. Results are compared and the best of all five alloys is fixed. From the results, the appropriate alloy for the production of turbine blades is suggested.

Key words: Nickel Alloys, Ansys

I. Introduction

Gas, or combustion, turbines were originally developed in the 18th century. The first patent for a combustion turbine was issued to England's John Barber in 1791. Patents for modern versions of combustion turbines were awarded in the late nineteenth century to Franz Stolze and Charles Curtis, however early versions of gas turbines were all impractical because the power necessary to operate the compressors outweighed the amount of power generated by the turbine. To achieve positive efficiencies, engineers would have to increase combustion and inlet temperatures beyond the maximum allowable turbine material temperatures of the day. Although some prototype combustion turbine units were designed, the developments that led to their practical use were a result of World War II military programs. Most developments in the 1950s and 1960s were geared towards gas turbines for aircraft use. R&D received a boost when turbofan engines were employed by commercial aircraft as well as for military use. In a gas turbine engine, a single turbine section is made up of a disk or hub that holds many turbine blades. That turbine section is connected to a compressor section via a shaft, and that compressor section can either be axial or centrifugal. Air is compressed, raising the pressure and temperature, through the compressor stages of the engine. The pressure and temperature are then greatly increased by combustion of fuel inside the combustor, which sits between the compressor stages and the turbine stages. That high temperature and high pressure fuel then passes through the turbine stages. The turbine stages extract energy from this flow, lowering the pressure and temperature of the air, and transfer that energy to the compressor stages along the shaft. This is process is very similar to how an axial compressor works, only in reverse. The number of turbine stages varies in different types of engines, with high thrust, high bypass ratio, engines tending to have the most turbine stages. The number of turbine stages can have a great effect on how the turbine blades are designed for each stage. A turbine blade is the individual component which makes up the turbine section of a gas turbine. The blades are responsible for extracting energy from the high temperature, high pressure gas produced by the combustor. The turbine blades are often the limiting component of gas turbines.[1] To survive in this difficult environment, turbine blades often use exotic materials like super alloys and many different methods of cooling, such as internal air channels, boundary layer cooling, and thermal barrier coatings.

II. Failure of Turbine Blades

Turbine blades are subjected to very strenuous environments inside a gas turbine. They face high temperatures, high stresses, and a potentially high vibration environment. All three of these factors can lead to blade failures, which can destroy the engine and turbine blades are carefully designed to resist those conditions. Turbine blades are subjected to stress from centrifugal force (turbine stages can rotate at tens of thousands of revolutions per minute (RPM)) and fluid forces that can cause fracture, yielding or creep failures. Additionally, the first stage (the stage directly following the combustor) of a modern turbine faces temperatures around 2,500 °F (1,370 °C) up from temperatures around 1,500 °F (820 °C) in early gas turbines.

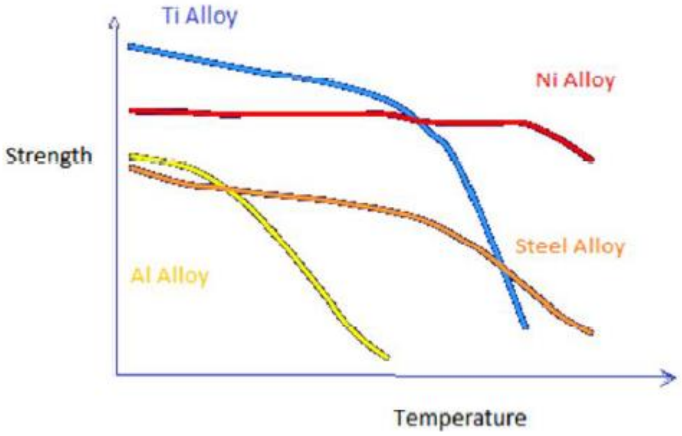
Modern military jet engines, like the Snecma M88, can see turbine temperatures of 2,900 °F (1,590 °C). Those high temperatures weaken the blades and make them more susceptible to creep failures. The high temperatures can also make the blades susceptible to corrosion failures. Finally, vibrations from the engine and the turbine itself can cause fatigue failures.

III. *Materials*

Material improvements have often been marked by iterative advancements through the years. In the 1950sand 1960s, materials were often selected from available in-house steam turbine and jet engine experiences. [1] Inconel-750 (Nickel alloy) is better due to its better handling of elevated temperatures and stress. It can be used efficiently in combustion chambers in engine. When TBC is applied to it, it helps with stress withstanding ability. [2] In Udimet 720 susceptible to microstructures changes, this can degrade their performance leading to intergranular creep failure. In addition to, creep failure; blades can also be susceptible to fatigue failure when high temperature are involved. Detrimental changes in microstructure includes coarsening, agglomeration & rafting of the γ' phase, formation of γ'- denuded zones alongside grainsized boundaries and precipitation of intermetallic compounds particularly $\sigma \& \eta - phase.$ [3] For alloy 720 Li could be observed that at room temperature 400 °C- 500°Cγ' represents the initially softer phase as theγ phase during the onset of yielding. At these temperatures, significant hardening occurs, in the γ' phase during yield and as plasticity progresses load load is transferred back in opposite direction [3]. However, differences between industrial gas turbines and these other types of turbines eventually required that their material paths diverge. For example, aerospace turbines operate under significantly different conditions because turbojets operate in relatively pristine environments and situations for which light weight is a benefit.[4]For Inconel 600 due to high temperature & a surrounding of oxygen and nitrogen and hydrogen gases the material lose its plastic properties. Hence it requires a thorough analysis of corrosion environment.[5] Nitrided Inconel 718 was observed to increase in hardness which dependent on process time & temperature. The surface roughness increased with the increment of the nitriding time & temperature. The plasma nitriding process considerably. Reduced friction coefficient with include were improved with increases of the nitriding time & temperature. A super alloy or high-performance alloy is an alloy that exhibits excellent mechanical strength and creep resistance at high temperatures, good surface stability, and corrosion and oxidation resistance. Super alloys typically have a matrix with an austenitic face-centred cubic crystal structure. A super alloy's base alloying element is usually nickel, cobalt, or nickel-iron. Super alloy development has relied heavily on both chemical and process innovations and has been driven primarily by the aerospace. Typical applications are in the aerospace, industrial gas turbine and marine turbine industry, e.g. for turbine blades for hot sections of jet engines, and bi-metallic engine valves for use in diesel and automotive applications. The development of super alloys in the 1940s and new processing methods such as vacuum induction melting in the 1950s greatly increased the temperature capability of turbine blades. Further processing methods like hot isostatic pressing improved the alloys used for turbine blades and increased turbine blade performance. Modern turbine blades often use nickel-based super alloys that incorporate chromium, cobalt, and rhenium. Aside from alloy improvements, a major breakthrough was the development of directional solidification and single crystal production methods. These methods help greatly increase strength against fatigue and creep by aligning grain boundaries in one direction or by eliminating grain boundaries all together.

IV. Strength versus Temperature

The strength of most metals decreases as the temperature is increased, simply because assistance from thermal activation makes it easier for dislocations to surmount obstacles.



However, nickel based super alloys containing γ', which essentially is an intermetallic compound based on the formula Ni3(Al,Ti), are particularly resistant to temperature. Ordinary slip in both γ and γ' occurs on the {111}<110>. If slip was confined to these planes at all temperatures then the strength would decrease as the temperature is raised. However, there is a tendency for dislocations inγ' to cross-slip on to the {100} planes where they have a lower anti-phase domain boundary energy. This is because the energy decreases with temperature. Situations arise where the extended dislocation is then partly on the close packed plane and partly on the cube plane. Such a dislocation becomes locked, leading to an increase in strength. The strength only decreases beyond about 600oC whence the thermal activation is sufficiently violent to allow the dislocations to overcome the obstacles. To summarise, it is the presence of γ' which is responsible for the fact that the strength of nickel based superalloys is relatively insensitive to temperature.

V. applications of nickel based alloys

A major use of nickel based super alloys is in the manufacture of aero engine turbine blades. A single crystal blade is free from γ/γ’ grain boundaries. Boundaries are easy diffusion paths and therefore reduce the resistance of the material to creep deformation. The directionally solidified columnar grain structure has many γ grains, but the boundaries are mostly parallel to the major stress axis; the performance of such blades is not as good as the single-crystal blades. However, they are much better than the blade with the equiaxed grain structure which has the worst creep life. One big advantage of the single-crystal alloys over conventionally cast polycrystalline super alloys is that many of the grain boundary strengthening solutes is removed. This results in an increase in the incipient melting temperature. A higher heat-treatment temperature allows all the γ' to be taken into solution and then by aging, to precipitate in a finer form. Super alloy blades are used in aero engines and gas turbines in regions where the temperature is in excess of about 400^0C, with titanium blades in the colder regions. This is because there is a danger of titanium igniting in special circumstances if its temperature exceeds 400^0C. The single crystal alloys can therefore be heat treated to at temperatures in the range 1240-1330°C, allowing the dissolution of coarse γ' which is remnant of the solidification process. Subsequent heat treatment can therefore be used to achieve a controlled and fine-scale precipitation of γ'. The primary reason why the first generation of single crystal super alloys could be used at higher temperatures than the directionally solidified ones was because of the ability to heat treat the alloys at a higher temperature rather than any advantage due to the removal of grain boundaries.

VI. Analysis in Ni alloys

A static structural analysis determines the displacements, stresses, strains, and forces in structures or components caused by loads that do not induce significant inertia and damping effects. Steady loading and response conditions are assumed; that is, the loads and the structure's response are assumed to vary slowly with respect to time.

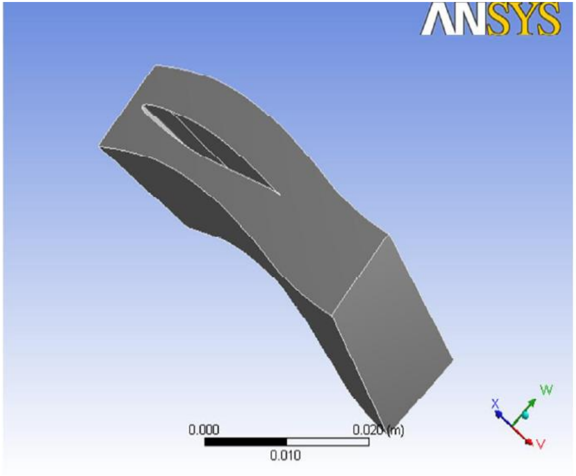
Table 1: Material composition of different Nickel Alloys

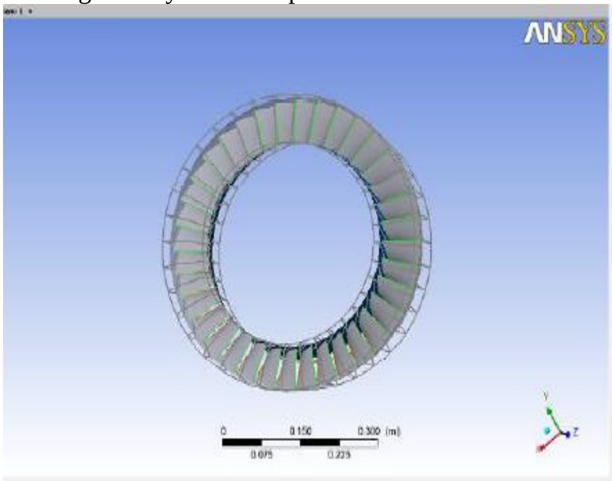
Materials / Alloy	Inconel 600	Inconel 718	Alloy 720 Li	RR 1000	Udimet 720
Ni	72	50-55	52.5	54	55
Cr	14-17	17-21	19	14.35-15.35	18
Mo	Nil	1	Nil	14-19	14.8
Ti	Nil	0.65-1.15	0.9	3.45-4.15	5
Others	11-14	31.25-22.85	27.6	7.5-14.2	7.2

A static structural analysis can be either linear or nonlinear. All types of nonlinearities are allowed - large deformations, plasticity, stress stiffening, contact (gap) elements, and hyper elasticity and so on. This focuses on linear static analyses, with brief references to nonlinearities. Details of how to handle non linearity are described in Nonlinear Controls. The flow analysis for the turbine blade was done in ANSYS Turbo Grid and CFX. The turbine blade used in this project is taken from the Turbine NACA series 65212. From NASA website, this blade dimensions are taken and used in ANSYS Turbo Grid. Every single blade makes an angle of 0.98 between hub and shroud. The geometry was done then. The finished model was then sent for meshing in the same Turbo Grid. Here mesh size is 0.01in range. The mesh model is T grid mesh. After meshing the blade, it was sent to CFX Pre turbo machinery. The boundary conditions given in turbo machinery for the blade are Revolution 36000rpm; medium air; mass flow rate100 g/sec temperature1200*c. After giving these boundary conditions, the blades with these conditions run for the checking of turbulence and continuity equations. The output of the boundary conditions was then sent to the solver in CFX. In solver, the boundary conditions of the pre-processor were checked for errors. Since there was no error, the solver automatically solves the given boundary conditions. The output was sent to CFX post processor.

VII. Static Structural Analysis

The structural analysis was done in ANSYS Workbench and it was Static Structural Analysis. At first the material that we have decided is entered to the engineering data. The required details of the material (Ni alloy) like Young's Modulus, Poisson ratio and density were entered. In the geometry the hub position was taken as fixed and the pressure force was applied towards the leading edge. Now the structural Analysis was done with the above conditions. The result of deformation, stress and strain for the geometry with the specified material were stored.





Then the whole Structural Analysis process was repeated for all the other four Ni alloys and the results are stored separately for every Material. This package of results shows us the stress level, deformation and strain throughout the turbine blade section for every material at 1200^0c.

VII. Conclusions

Two set of results each having five results, were verified separately for 800*c and 1200*c and from those results the best of all five Ni alloys is determined. The alloy which had very low deformation, very low stress distribution in the blade region is suggested as the suitable alloy among these five alloys for turbine blade material selection.

Table 2: Elongation produced after application of shear stress at different temperatures.

Sl.No.	Material	Temperature Degree Celsius	Maximum Equivalent stress (Pa)	Maximum shear stress (Pa)	Maximum Elongation (m)
1	Alloy 720 Li	800	$2.9757x\ 10^{8}$	$1.5059x\ 10^{8}$	0.0185
		1200	$2.5894x\ 10^{8}$	$1.3103x\ 10^{8}$	0.0164
2	Inconel 600	800	$3.0301x\ 10^{8}$	$1.5337x\ 10^{8}$	$2.0398x\ 10^{-5}$
		1200	$2.6367x\ 10^{8}$	$1.3345x\ 10^{8}$	$1.775x\ 10^{-5}$
3	Inconel 718	800	$3.0301x\ 10^{8}$	$1.5337x\ 10^{8}$	0.23
		1200	$2.6367x\ 10^{8}$	$1.3345x\ 10^{8}$	0.17
4	RR 1000	800	$2.9388x\ 10^{8}$	$1.4872x\ 10^{8}$	0.0191

		1200	$2.5572x\ 10^8$	$1.2941x\ 10^8$	0.0166
5	Udimet 720	800	$3.0481x\ 10^8$	$1.5430x\ 10^8$	0.0966
		1200	$2.6524x\ 10^8$	$1.3427x\ 10^8$	0.0174

From the tabulations given above, it can be seen clearly that, the alloy RR 1000 has given a better overall result when comparing to others. And Incomer 600 shows the minimum elongation for any temperature, but not in other properties. So aircrafts for short range purpose can choose Inconel 600 as the turbine blade material and for long range, RR 1000 is the best choice.

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