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Analysis and structural design of various turbine blades under variable conditions: A review

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Abstract. This paper presents a review study for energy-efficient gas turbines (GTs) with cycles which contributes significantly towards sustainable usage. Nonetheless, these progressive engines, operative at turbine inlet temperatures as high as 1600°C, require the employment of highly creep resistant materials for use in hotter section components of gas turbines like combustion chamber and blades. However, the gas turbine obtain its driving power by utilizing the energy of treated gases and air which is at piercing temperature and pushing by expanding through the several rings of steady and vibratory blades. Since the turbine blades works at very high temperature and pressure, high stress concentration are observed on the blades. With the increasing demand of service, to provide adequate efficiency and power within the optimized level, turbine blades are to be made of those materials which can withstand high thermal and working load condition for longer cycle time. This paper depicts the recent developments in the field of implementing the best suited materials for the GTs, selection of proper Thermal Barrier Coating (TBC), fracture analysis and experiments on failed or used turbine blades and several other designing and operating factors which are effecting the blade life and efficiency. It is revealed that Nickel based Superalloys were promising, Cast Iron with Zirconium and Pt-Al coatings are used as best TBC material, material defects are the foremost and prominent reason for blade failure.

Keywords: gas turbine blade; turbine inlet temperature; thermal barrier coating; finite element analysis; failure analysis; blade efficiency; metallurgical analysis

1. Introduction

Modern combined cycle gas-turbine (CCGT) engines require a fundamental increase of turbine inlet temperatures (TIT) for achieving the peak efficiency. This thermodynamic trend resulted in a raised couple temperature, enhanced diffuse casualty and hot-corrosion resistance of the engine materials. In specific, the gas-turbine (GT) blades work under the most exhausting conditions of temperature. However, to enhance the properties of blades, alloying elements are blended with the blade material. The most preferably used alloys are Nickel-based super alloys which substantially supports an excellent high-temperature creep resistance, thermal stability, high tensile strength,

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micro-structure stability at high temperature and resistance towards oxidation and hot corrosion (Madhu 2015, Khawajah and Motamedi 2014, Kumar and Pandey 2016, Ujede and Bhambere 2014).

Moreover, modern gas turbine engines are generally considered to exhibit high level of reliability with low failure rates. The failures of the turbine blades may be subjected to several reasons i.e. mechanical failure, hot corrosion failure, high temperature damage, creep and fatigue. These damages will reduce the life of turbine blade which will directly affect the working cycles (Carter 2005).

Keeping in view of the above facts related to the failure of turbine or turbine blades, the material must be chosen with a meticulous judgment for the gas turbine as the blade directly takes the hot steam on them at a very high speed for almost 8 to 10 hours in a day to achieve rotation of about 15000 RPM, in order to produce roughly 980 Megawatt power every day to meet the growing need of electricity (Huda 2017).

Nevertheless, Nickel based super alloys and Titanium based Alloys are preferably used because of its balanced and stable nature and is most suited materials for making the turbine blades after being tested under several testing criteria by Ravindra and Raju (2017) as well as several other researchers. In this paper, the outcomes of some of the studies are reviewed, which are concerned with the implementation of the different suitable material, thermal barrier coating and its advancements, first and second stage turbine blade failure analysis and cooling aspects of turbine blade for making it optimal for usage.

Moreover, in the field of aviation, commercial demands make it necessary for modern gas turbine engines to function under extreme conditions, working even beyond the manufacturer's recommended time period. In any of such instances, critical sections of the engine will eventually be detrimentally affected which is the case of high pressure turbine (HPT), where temperatures are the highest in the entire engine (Brandao *et al*. 2016).

Metallurgical examination can be very effective in determining whether the failure is related to material defects, machining marks, poor surface finish, initial flaws or heat treatment (Mazur *et al*. 2004, Hon *et al*. 2002, Poursaidi *et al*. 2008, Ravi *et al*. 2017). However, the examination does not take account of possible variations, from the design, in the mechanical behavior and characteristics of the blade and these variations may be directly linked to the mechanism of failure.

Several authors used Finite Element Method (FEM) as a tool for their respective analysis work in their research. The finite element method is a numerical analysis technique for obtaining approximate solution to a class of problems governed by elliptical partial differential equation. Such problems are called boundary value problems. It has now become a very important and powerful tool for numerical solution of wide range of engineering problems. The Finite Element Methods are being used for the analysis of structures solids of complex shapes and complicated boundary conditions (Kumar and Rose 2015). The FEM is one of the prominent tool that is used by several researchers here for various analysis. The FEM were used to determine the steady-state stresses and dynamic characteristics of the turbine blade (Hou *et al*. 2002), level of deformation due to creep and fatigue (Brandao *et al*. 2016), three dimensional external fluid flow and heat transfer simulation (Reyhani *et al*. 2013, Kim *et al*. 2010), propagation and measure of inter-crystalline cracks, thermal fatigue, thermomechanical stress failure (Mazur *et al*. 2005) along with other mechanical, metallurgical and thermal properties.

Table 1 Comparison of the adopted three materials on various factors (Madhu 2015)

RPM	29000		
Materials	NIMONIC 90	MAR M-247	INCONEL 718
Max working stress (MPa)	557.198	761.774	731.72
Max strain	0.016629	0.007283	0.006681
Temperature at max working stress		725°C	
Yield strength (MPa)	580	800	852
UTS (MPa)	816	1002	933
Factor of safety	1.040	1.050	1.164
Fatigue life cycles	8461	13444	29258

2. Advancements in suitable material selection

Furthermore, material selection is the most important parameter for analysis. Choosing the right material for any component depends particularly on cycle time of operation, ambient temperature and pressure. In case of turbine, the material selection is even more important as turbine works under severe operating conditions. Below paragraphs illustrates several developments related to an appropriate selection of materials.

Madhu (2016) analyzed the stress and carried out the life estimation of gas turbine blade with the use of the following materials i.e. NI-90, MAR-247 and Inconel-718, under various load conditions and fatigue life was calculated using coffin Manson equation. The operating speed was kept constant as 29000 RPM at maximum possible temperature. Author found Inconel-718 to be the best suitable material as when compared to the rest others. Table 1 shows the comparison of the adopted three materials on various factors.

Similarly, Mazarbhuiya and Pandey (2017) analysed stresses and elongation of blades for ten different materials used for manufacturing of turbine blades using Finite Element Analysis software ANSYS. They observed that root of the blade was subjected to maximum stress for all blade material while the blade made up of MAR – M246 possessed less stress and deformation.

On the other hand, Chintala and Gudimetla (2014) used the concept of Reverse Engineering and Finite Element Analysis to design and test a turbine blade, whether some materials are under the safe limits or not. They observed that the centrifugal stresses in case of Al, Mg and Ti was found within the safe limits and Ti was obtained to be the best suited material having Yield Strength of 830 MPa.

Table 2 The results of all three materials after analysis (Ravindra and Raju 2017)

Materials	Total deformation (mm)		Von Mises Stress (Mpa)		Equivalent elastic strain (mm/mm)		Thermal strain (mm/mm)	
	Min	Max	Min	Max	Min	Max	Min	Max
Ti6Al4V	0	0.66784	0	107.37	2.253×10^{-4}	1.1265×10^{-3}	0	0
Structural steel	0	2.3294	0	8361.4	0	4.4757×10^{-2}	9.36×10^{-3}	9.36×10^{-3}
Ti8Al1Mo1V	0	1.8326	0	2941.7	0	3.4002×10^{-2}	7.7832×0^{-3}	7.7832×10^{-3}

In actual practice Ti is not used in its elemental stage but its alloys are used. In this area, Ravindra and Raju (2017) opted three different materials which were considered to be suitable for manufacturing turbine blade namely Titanium alloys Ti6Al4V, Ti8Al1Mo1V and Structural Steel which were analyzed separately for Total Deformation, Max-Von Mises Stress and Thermal Strain. Analysis depicted that all the materials were safe to use. However, Ti6Al4V was found to be the best suited material amongst other, as it has the least deformation and thermal strain under same operating and ambient conditions. Table 2 shows the results of all three materials after analysis (Ravindra and Raju 2017).

Moreover, Khawaja and Motamedi (2014) performed an extensive study on 21 types of Inconel and 12 types of Nimonic Nickel based Superalloys. The analysis was carried out in two stages, where only 4 materials were analyzed in first stages and rest were chosen for second stage. Amongst all the type of materials used, Nimonic 115 was found to be the best suited material. Fig. 1 shows the methodology followed by Khawaja and Motamedi for selecting the suitable material in their research work. In addition to this, Kumar and Pandey (2016) also analyzed three materials namely Nimonic 80A, Superalloy X and Inconel 625 at three different rotating speeds i.e. 20000, 40000 and 60000 RMP respectively. The analysis was done for centrifugal forces, stress and deformation. Similarly, Gurajarapu *et al*. (2014) also conducted the same kind of experiment for selecting the suitable material on a turbine blade specifically for a marine gas turbine engine and observed a similar trend of result. Table 3 shows the results for total deformation and equivalent stress distribution in turbine blades made of different materials at various speeds.

Several factors are to be considered for designing the turbine blades with the application of best suited materials. Most of the researches shows the use of Nickel based and Titanium based super alloys for the design of turbine blades along with several other material such as Hastealloy (Saini

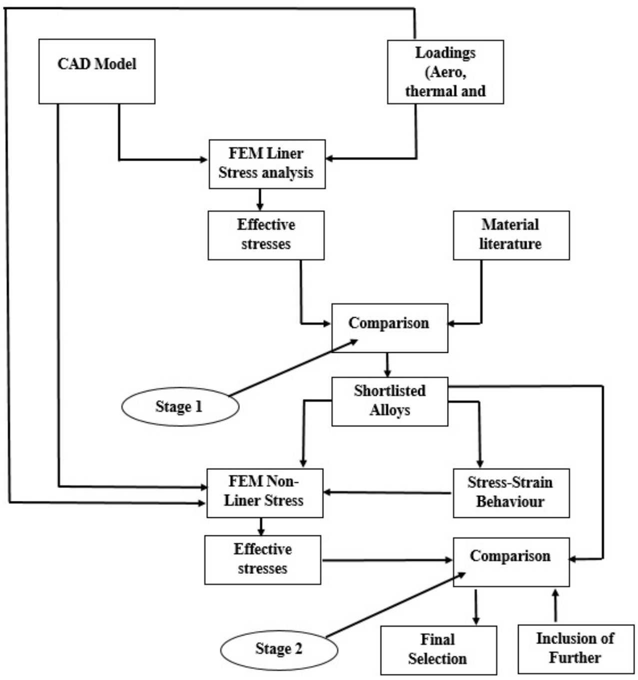


Fig. 1 Roadmap to Selection Methodology (Khawaja and Motamedi 2014)

Table 3 Total deformation and equivalent stress distribution in turbine blades made of different materials at various speeds (Kumar and Pandey 2016, Gurajarapu *et al*. 2014)

Materials	RPM [High for General or Aircraft Applications; Low for Marine Applications]		Max deformation (mm)	Von Mises Stress (MPa)
Super Alloy X	Low	4000	0.39	267.72
		6000	1.01	624.44
		9000	2.3	965.59
	High	20000	2.927	17629
		40000	11.629	70100
		60000	26.132	151550
Nimonic 80 A	Low	4000	0.4	292.51
		6000	1.02	687.98
		9000	2.408	1054.7
	High	20000	2.931	19958
		40000	11.65	79393
		60000	26.182	1718450
Inconel 625	Low	4000	0.44	292.46
		6000	1.12	682.73
		9000	2.64	1045.8
	High	20000	3.199	18771
		40000	12.718	75468
		60000	28.583	169630

and Shandil 2015), Superalloy-X (Gurajarapu *et al*. 2014), MAR 247 (Madhu 2016) etc. It can be derived from most of the studies, that under a practical working conditions, the Nickel based superalloys generally shows better stability, durability and longevity when they are used to design the turbine blades specially under steady state loading conditions.

On the other hand, Chintala and Gudimetla (2014) analyzed very common metals that could be used to make the turbine blades. They suggested that out of all the single metals, Titanium is the best material to be used for the manufacturing of gas turbine blade. Nevertheless, Caron and Khan (1999) studied the use of Rhenium in the blade manufacturing and the development in different stages of turbine blade was observed. They observed that the overall performance of second and third generation has been improved significantly by adding the increased amount of Rhenium.

3. Analysis regarding advances in thermal barrier coating

Despite of the fact that material blending in turbine blade plays a vital role towards the blade efficiency and performance, some other factors like Thermal barrier coating is quite an important aspect to be studied, since the thermal resistance is also a prominent parameter during the running of turbine blades under high temperatures and drastic conditions. An appropriate coating is essential for enhancing the life of the blade. Owing to which, thermal barrier coating on the blade is adopted to reduce the temperature of the underlying substrate and also to provide protection against oxidation and hot corrosion. This section discusses several advancements in the field of thermal barrier coating and ways to reinforce their life and temperature resisting quality.

The Thermal barrier coating was carried out using the platinum aluminum or platinum chromium compound which constitutes the top coat of TBC Rani *et al*. (2017).

It was also suggested that cast iron along with Zirconium coating (Ujede and Bhambere 2014) is more beneficial due to low stress displacement and also with manufacturing ease.

Similar kind of approach was adopted by Zhu and Ma (2014) where they performed a heat treatment process on a specimen of turbine blade coated with plasma sprayed thermal barrier coating for 10 hrs keeping the heating rate at 600°C per hour and cooling rate of about 200°C per hour. They investigated the micro-structural and material properties of blade using Scanning Electron Microscopy and Indentation. As a result of which it was observed that the microstructure of ceramic coating would continuously change due to the grain growth and narrowing of cracks at high temperature after the heat treatment process.

Additionally, Reyhani *et al*. (2013) also carried out an experimental setup using thermal barrier coating on the turbine blade and concluded their work that adding 300 micrometer layer of thermal barrier coating on the blade leads to increase in life by 9 times. A general guidelines adopted by Reyhani *et al*. (2013) for life estimation procedure is depicted in Fig. 2. On a similar note, Ujede and Bhambere (2014) concluded that the Cast Iron with Zirconium coating on the blade made of Inconel 718 is the best suited TBC due to its low stress displacement and also stated about the enhancing thermal properties of IN 625.

On the other hand, Rani *et al*. (2017) mentioned that the outer coating of the blade is rich in Platinum aluminum compound. As the blade comes in contact with air and hot gases, the initial degradation occurs due to oxidation of the aluminum (from the platinum aluminum coating) forming Aluminum Oxide on the surface, which is quite visible by its significant red colour. Further this Al_2O_3 is removed eventually due to erosion that leads to increase in the oxygen percentage upto 26.64% and decrease in the percentage of aluminium by 10%. The remaining Platinum in the platinum aluminium outer coating diffusers are decomposed to intermediate layer to form γ’ Phase.

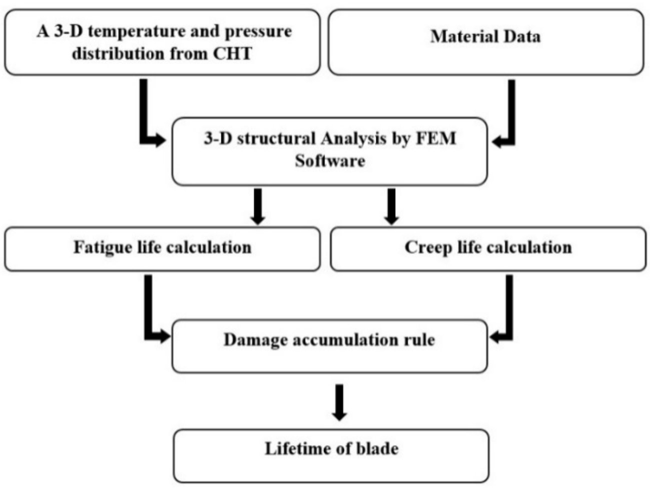


Fig. 2 Flow chart of the life estimation procedure (Reyhani *et al*. 2013)

On the other hand, Rani *et al*. (2017) mentioned that the outer coating of the blade is rich in Platinum aluminum compound. As the blade comes in contact with air and hot gases, the initial degradation occurs due to oxidation of the aluminum (from the platinum aluminum coating) forming Aluminum Oxide on the surface, which is quite visible by its significant red color. Further this Al_2O_3 is removed eventually due to erosion that leads to increase in the oxygen percentage upto 26.64% and decrease in the percentage of aluminum by 10%. The remaining Platinum in the platinum aluminum outer coating diffusers are decomposed to intermediate layer to form γ' Phase.

Moreover, Li *et al*. (2017) performed a comparative research on the design of thermal barrier coating thickness for gas turbine blade based on typical finite element analysis methods. After thorough study and research, it was concluded that the blade platform should be coated with thick thermal coating as thick as possible and the blade tip as well as the bottom area requires thick coating at the middle region. It was also concluded that the thermal insulation capability and stress level within the coating on the blade airfoil was enhanced with the increase of topcoat thickness. An optimized design procedure for TBC thickness was presented by Li *et al*. (2017) and is depicted in Fig. 3.

Similarly, Saini and Shandil (2015) carried out a thermal analysis of turbine blade made up of Hastealloy-X over which two types of TBCs were applied. First is partially stabilised Zirconium and second is Lanthanum Magnesium Hexaaluminate. Authors observed that under applied thermal loading conditions, 200 micron thick Zirconia coating used with 150 microns NiCrAlY layer was capable to reduce steady state temperature by 35.6%, steady state top surface heat flux by 15% and 3.72% to be more effective than equal thickness of Lanthanum Magnesium

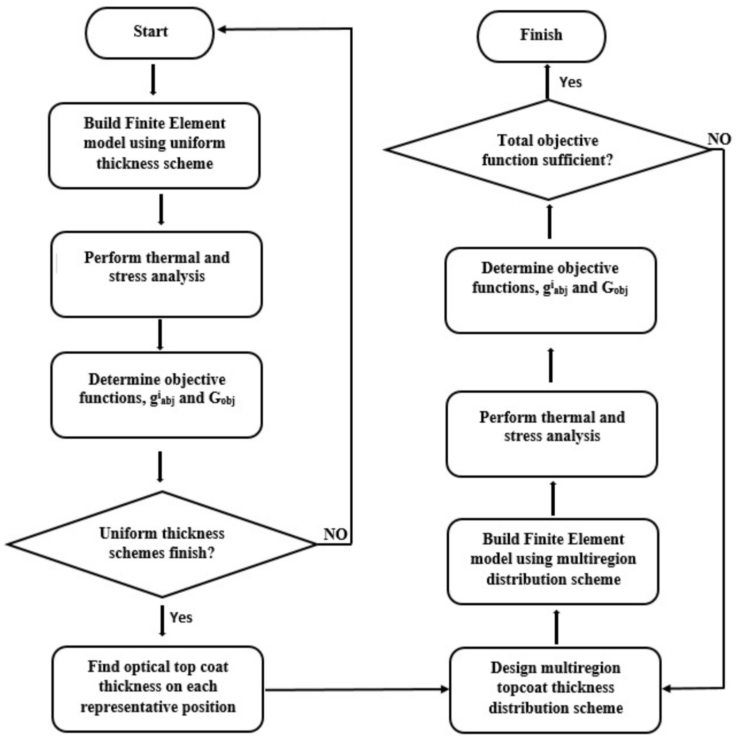


Fig. 3 Optimization design procedure for TBC thickness (Li *et al*. 2017)

Hexaaluminate coating. They concluded that the thin films of zirconia could be more durable than lanthanum aluminate coatings in high flux working conditions.

In a similar kind of analysis, Abid and Khan (2018) studied the thermal stresses and effects of different thermal barrier coating blade base alloys using CATIA and ANSYS software. They revealed that the best coating is done using air-plasma method with three different layer i.e., Inconel 718 followed by NiCoCrAlY and $La_2Ce_2O_7$ on the top, which was suggested to be the best feasible option for high operating temperatures.

Following a different and more experimental approach Ali *et al*. (2018) investigated various possibilities of failure mechanisms in the Thermal Barrier Coating (TBC) exposed to high operating temperature of a gas turbine first stage blade. The blade was made up of Nickel based Superalloy having directionally solidified grain structure and coated with yttria-stabilized zirconia (EB-PVD Process) and Pt-Al bond coat (Electro-deposition process) as TBCs. Visual Inspection, Optical Microscopy, Scanning electron microscopy and Energy-dispersive spectroscopy had been used as characterisation tools on two cross-sectional samples that had been cut out at radial distance of 7 mm and 21 mm from the hub. The failure investigation reveals that the coating on the pressure side of the blade was severely damaged and coating degradation gradually increased from leading to trailing edge on the pressure side and occurred due to erosion, cracking and decohesion of coating which were the results of increase in the temperature and increase in the natural coating inclination towards the trailing edge. The widening of the inter-diffusion zone between the coating and the base alloy changed the composition and properties of the bond coat, also contributes in decohesion of coating.

Additionally, Marcin and Gupta (1994) reviewed the current state of the art of coating technology in the gas turbine. They mentioned several methods like chemical vapour deposition, physical vapour deposition, thermal spraying, diffusion and electroplating, which are used for coating the blade surfaces. They also suggested that the multi laminated coating like advanced titanium nitride erosion coating system could be beneficial. The physical and mechanical properties would be increased over the monolithic structure by forming thin multilayer composite structure. Fig. 4 represents a Schematic diagram of a TBC.

In the similar direction of selecting suitable TBC material and most effective method of coating, Saini *et al*. (2012) performed an extensive study on different kind of TBCs, amongst which

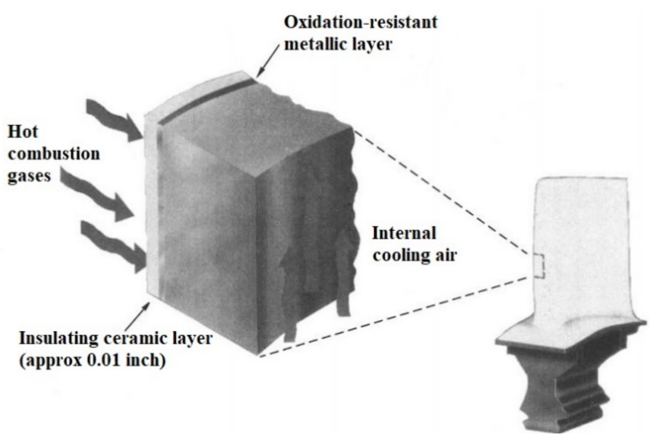


Fig. 4 Schematic diagram of a TBC (Marcin and Gupta 1994)

Zirconia had been their focus because of its low thermal conductivity, high chemical inertness and high toughness. Authors also studied several methods for applying TBC like plasma spraying, laser glazing, chemical vapour deposition and lased induced CVD processes. All the process had their fair shares of pros and cons but laser induced CVD process was found to give much better deposition rate and capable of producing thick and stable TBC.

4. Experimental observations for failure analysis

Despite of all the above parameters discussed, failure analysis is one of the crucial area to be considered with regard to the extent of durability of blade and damages that persist within it as well as its efficacy towards blade performance. Considering the same, several studies have been carried out which depicted a similar kind of results showing the crack pattern to be observed on both the tip of leading and trailing edge of the blades. It was also revealed that the failure doesn't occur due to material defects but mainly prevails due to oxidation of the thermal barrier coating on the top of blade which may lead to the occurrence of hot corrosion because of which propagation of cracks may develop leading towards blade failure. In general, it is noted that the leading edge is one of the hottest region of the blade where maximum stress occurs at the acute trailing corner. Keeping in view of this, regular maintenance of the turbine blade should be carried out with regard to the reinforcement of thermal barrier coating, inspection of cracks, extension of Fatigue creep and micro structural disorientation. This section demonstrates several outcomes of past studies regarding failure analysis of the blades with different material configurations under varying working conditions.

A very practical case was studied by Mazur *et al*. (2005) on a used turbine blade made of Inconel 738 and used for 70 MW production line. The blade was in service for 24000 hours at the peak temperature 1086°C. They performed grain structure evaluation, crack evaluation and stress analysis where the maximum tension stress in the blade airfoil was observed as 341 MPa.

Similarly, Ravi *et al*. (2017) performed a practical analysis on 3 specimens (each of 1 sq cm) taken from the trailing edge of turbine blade for evaluating the failure parameters. The turbine blade was made up of Ni-based super alloy Inconel 738. The authors concluded that the failure didn't occur due to material defects but due to surface degradation which was because of the oxidation of Pt-Al coating. Authors also indicated that a service and repair session could be implemented after 24000 hours of service which includes application of corrosion resistant alloy and friction dampers between the discs. Similar study was carried by Rao *et al*. (2014) where they obtained similar pattern of results. They proposed a necessity of regular maintenance after every 30,000 hours of service.

However, Hon *et al*. (2002) investigated fatigue failure of gas turbine using different mechanical analysis by employing Finite Element Modelling so as to ensure reliability and evaluating the robustness of the model. Where it was found that the peak stress shifted from trailing to leading edge with almost 10% variation in frequency between pre-stressed and damped condition.

Similarly, Poursaidi *et al*. (2008) performed an extensive failure analysis of a second stage blade (made of Inconel 738LC) in a gas turbine engine which was in service for 73500 hours. The blade failed due to multiple reasons like pitting, fatigue, crack initiation due to hot corrosion. Stress values at leading and trailing edge was obtained as 186.2 MPa and 127.2 MPa respectively, the values of which brought a conclusion to the authors that pitting was due to bending stresses,

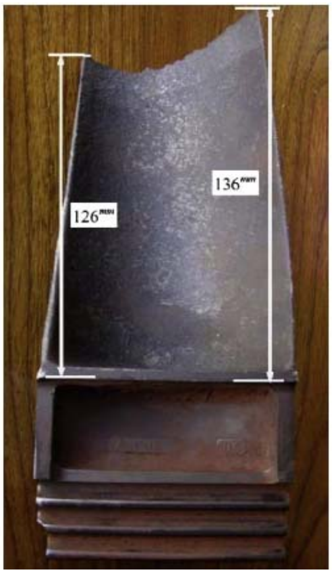


Fig. 5 the distances of the fracture surface from the platform blade edges (Poursaeidi *et al*. 2008)

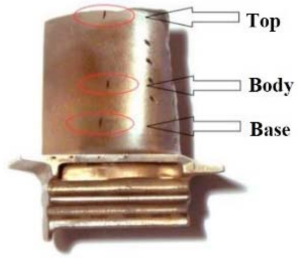
cracks were developed due to interdentride corrosion and propagated due to fatigue. Fig. 5 shows the actual fracture patterns which clearly reveal how the turbine blade generally gets affected during the operation.

On a similar note, Huda (2009) carried out a metallurgical failure analysis on a failed gas turbine blade (type Siemens V94.2 KWU). After examining the author concluded that the trailing edge of the blade got failed due to creep damage. He also recommended that more efficient blade cooling and TBC should be applied to turbine blade especially at the transverse section of the trailing edge. He further suggested that the alloy composition of the blade should be readjusted, thereby reducing cavity and creep.

Similarly, Brandao *et al*. (2016) performed a Finite Element analysis for High Pressure Turbine (HPT) Blade of an Airplane gas turbine engine. They predicted the life of turbine bladeas well as analysed the creep behaviour which ultimately leads to the degradation of blade surface. Authors acquired scrap turbine blade from the commercial airline company where they found that the chemical composition changes from top body to base of the degraded turbine blade after operating for 3,000 cycles. Fig. 6 clearly indicates the variation in chemical compositions during its performance.

Moreover, a special research for Indian Institute of Metals was carried by Salehnasab *et al*. (2017) regarding Failure Assessment of the First Stage Blade of a Gas Turbine Engine. The 60 MW gas turbine engine experienced a forced break down because of extremely high vibrations and subsequent output power reduction. Evaluation of the microstructures of the root and tip of the damaged blade were carried out and it was observed that no significant change occurred in the microstructure. Metallurgical investigations for the damaged zones of the fractured blade showed high concentrations of iron deposited near the fractured surface. The morphology of the fractured surface depicted a semi-brittle fracture due to the impact of the liberated components of the turbine engine on the blades.

On a more deepened approach to understand the behavior of crack propagation internally



	Al	Cr	Co	Ni	Ta	Fe	Pt
Top	3.36	1.99	8.68	74.87	2.27	-	8.84
Body	12.16	2.28	7.34	64.42	-	0.31	13.49
Base	2.53	0.59	7.06	64.91	-	-	24.91

Fig. 6 HPT blade section shows the variation in chemical compositions during its performance (Brandao *et al*. 2016)

Kanesund *et al*. (2019) examined two turbine blades made up of Inconel 792 for deformation and damage mechanism after service exposure under engine condition typical for industrial usage. Blade samples had been cut from the area around the cracks on the blade and make them gone through various mechanical and chemical processes for preparing the samples for further experimental procedures. The samples then being studied in two different field emission gun scanning electron microscope (FEG-SEM) namely Hitachi SU70 and Zeiss Merlin. An angular selective backscatter electron detection system (ASB Detector) used as an image detector. Electron channelling contrasting imaging (ECCI) used for detecting crystallographic defect that produced a distortion in the lattice or any sub-grain dislocation. Electron back-scattering diffraction (EBSD) technique was used for mapping out the grain orientation and disorientation, if exists. The chemical analysis had been performed here with EDS and WDS detectors. They found out the failure of the blades is mechanical and chemical damage where type-I hot corrosion and creep made the grain boundaries weak and brittle making them two dominant damage mechanism. Most of the cracks were found to be propagated inter-crystalline down to the cooling holes on both pressure and suction side. The combined effects had observed to shorten the turbine blade life dramatically.

On the other hand, Cowles (1996) reviewed various industrial approaches for assessing and improving the high cycle fatigue resistance quality in modern aircraft turbine blades. He addressed several complicating factors that affect the HCF material capability where the author mentioned several significant areas on account of which developments like stress ratio effect, crack behaviour, crack closure treatment, threshold modelling and crack initiation and growth, were actually required for which an appropriate experimental methods will be necessary to ensure successful implementation.

However, Bons (2010) and Huda (2017) reviewed several research works on surface roughness effect on turbine blade. Bons (2010) concluded that accurate models for predicting roughness effects on profile losses and surface heat transfer are still a subject to discover. The predominant reason for this can be correlated to the parameters such as size, shape, spacing and blade location for determining adequate characterize roughness. Whereas, Huda (2017) emphasized on the selections of materials which is found suitable for making the hot section of turbine blades. He also recommended to develop super alloys based on higher melting temperatures (such as molybdenum-based super alloys) for future combined cycle gas turbine (CCGT) plants with a possibility of operation at Turbine inlet temperature (TIT) > 1600°C.

5. Conclusions

On reviewing several past research studies concerning advancements and analysis related to several parameters (design, material selection, top coating, failure and other key factors) for different types of gas turbine blade subjected to varying operating conditions, it is clear that a combination of all the above mentioned parameters are quite necessary for ensuring high efficiency and improved blade life. The conclusions derived from all the mentioned research works are as follows:

- Nickel based super alloys have been found to be the best suited material for turbine blades.
- Layering of blade surface with suitable coating supporting proper refractoriness has also been found to be crucial.
- Material defect was found out to be the primary reason for blade failure. Secondary reasons were creep and fatigue.
- Cast Iron with Zirconium and Pt-Al used as TBC gives an effective result towards enhancement of blade life.
- Suitable range of servicing time was to be after 24000 hrs to 30000 hrs of working cycle time.

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