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SOME STUDIES ON FAILURES IN GAS TURBINE BLADES – A REVIEW

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Abstract
Advancements made in the field of materials have contributed in a major way in building gas turbine engines with higher power ratings and efficiency levels. Improvements in design of the gas turbine engines over the years have importantly been due to development of materials with enhanced performance levels. Gas turbines have been widely utilized in aircraft engines as well as for land based applications importantly for power generation. Advancements in gas turbine materials have always played a prime role – higher the capability of the materials to withstand elevated temperature service, more the engine efficiency; materials with high elevated temperature strength to weight ratio help in weight reduction. A wide spectrum of high performance materials - special steels, titanium alloys and super alloys - is used for construction of gas turbines. Manufacture of these material soften involves advanced processing techniques. Other material groups like ceramics, composites and inter-metallic have been the focus of intense research and development; aim is to exploit the superior features of these materials for improving the performance of gas turbine engines. The materials developed at the first instance for gas turbine engine applications had high temperature tensile strength as the prime requirement. This requirement quickly changed as operating temperatures rose. Stress rupture life and then creep properties became important. In the subsequent years of development, low cycle fatigue (LCF) life became another important parameter. Many of the components in the aero engines are subjected to fatigue- and /or creep-loading, and the choice of material is then based on the capability of the material to withstand such loads. Coating technology has become an integral part of manufacture of gas turbine engine components operating at high temperatures, as this is the only way a combination of high-level of mechanical properties and excellent resistance to oxidation / hot corrosion resistance could be achieved. The review brings out a detailed analysis of the advanced materials and processes that have come to stay in the production of various components in gas turbine engines. While there are thousands of components that go into a gas turbine engine, the emphasis here has been on the main components, which are critical to the performance of the engine. The review also takes stock of the R&D activity currently in progress to develop higher performance materials for gas turbine engine application.

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Keywords: Gas turbines, material selection, Low cycle fatigue, creep-loading.

1. Introduction

1.1 Gas Turbine Working Principle

A schematic drawing of a simple gas turbine is shown in figure 1.1. The working principle behind the gas turbine is as follows. Ambient air is compressed in the compressor. This compressed air is directed to the combustion chamber. In the combustion chamber the compressed air is mixed with vaporized fuel and burned under constant pressure. This burning process results in a hot gas with high energy content. This hot gas is allowed to expand through the turbine where the energy in the gas is converted to a rotation of the turbine shaft. The turbine shaft powers both the compressor and a generator used to obtain electrical power from the gas turbine.

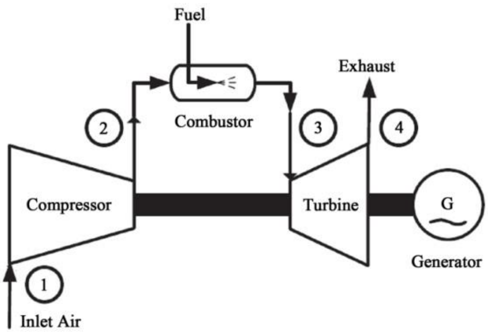

Fig: 1.1 – Gas Turbine Working Principle

1.2. Turbine blade

Super alloys were developed since the second quarter of the 20th century as materials for elevated temperature applications and can be divided in three groups: nickel-base super alloys, cobalt-base super alloys and iron base super alloys. Gas turbine blades are principally made of nickel-base and cobalt-base super alloys. The main reason for the existence of super alloys is their outstanding strength at elevated temperatures, which make them suitable for the fabrication of gas turbine components. During the operation of power generation gas turbines, the blades and other elements of hot gas path undergo service-induced degradation, which may be natural or accelerated due to different causes.

The degradation or damage may have a metallurgical or mechanical origin and results in reduction of equipment reliability and availability. To identify the causes of the blade failures, a complete investigation has to be carried out, integrating both the mechanical analyses and metallurgical examination. Metallurgical examination can be very effective in determining whether the failure is related to material defects, mechanical marks, poor surface finish, initial flaws or heat treatment.

There are different factors, which influence blade lifetime, as design and operation conditions but the latter are more critical. In general, most blades have severe operation conditions characterized by the following factors

1. Operation environment (high temperature, fuel and air contamination, solid particles, etc.).

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2. High mechanical stresses (due to centrifugal force, vibratory and flexural stresses, etc.).
3. High thermal stresses (due to thermal gradients).

Typically there are acting two or more factors simultaneously causing reduction of blade lifetime. The type of damage, which occurs in gas turbine blades and nozzles after a service period, can be divided into :

1. External and internal surface damages (corrosion, oxidation, crack formation, erosion, foreign object damage and fretting).
2. Internal damage of microstructure, such as c0[Ni3(Al,Ti)] phase aging (rafting), grain growth, creep and grain boundary void formation, carbides precipitation and brittle phases formation.

Surface damage produces blades/nozzles dimensional changes, which result in operational stress increase and turbine efficiency deterioration. In service, blade material deterioration is related to the high gas temperature, high steady state load levels (centrifugal load) and high thermal transient loads (trips, start-ups and slowing downs). However, the degree of deterioration in individual blades differs due to several factors such as:

1. Total service time and operation history (number of start-ups, shut-downs and trips).
2. Engine operational conditions (temperature, rotational speed, mode of operation (base load, cyclic duty)).
3. Manufacturing differences (grain size, porosity, alloy composition, heat treatment).

The Inconel 738LC alloy commonly used for gas turbine blades is strengthened by precipitation of c0 phase. The micro structural changes due to blade operation at high temperature include irregular growing of particles (rafting) and formation of carbides in grain boundaries and matrix. This leads to alloy creep properties reduction.

In order to have an instrument for the deterioration evaluation of gas turbine blade alloy, it is necessary to associate the influence of service-induced micro structural degradation to the changes in mechanical properties. This can be used for monitoring and evaluation of extent and degree of material damage and lifetime consumed and to obtain recommendations for blade rejuvenation treatments, operation and reposition.

Application of effective methods of material deterioration evaluation can be used for practical lifetime prediction, just in-time blade rehabilitation (rejuvenation), safe and cost-effective lifetime extension and to avoid blade catastrophic failure. In the other hand most of gas turbo generators are used as an auxiliary compensator in power plants to generate electric power at the peak of load demand. Thus they often are utilized in discontinuous conditions of commissioning. This subject leads them to a lot of shocks and risks. Therefore it seems the failure analysis is a good manner for detecting the root causes. So according to the results of failure analysis, the gas turbine would be utilized by applying some new policies in the protected conditions. Often by using an intelligent mechanical analysis, the root causes of a failure could be revealed. Recently the computer programs and

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software packages are generalized to calculate the mechanical behaviour of gas turbine blades.

Literature review

Kermanpur, H. Sepehri Amin, S. Ziaei-Rad, N. Nourbakhshnia and M. Mosaddeghfar [1] have done failure analysis of Ti6Al4V gas turbine compressor blades. The failure mechanism of Ti6Al4V compressor blades of an industrial gas turbine was analysed by means of both Experimental characterisations and numerical simulation techniques. Several premature failures were occurred in the high pressure section of the compressor due to the fracture of the blade roots. Metallurgical and mechanical properties of the blade alloy were evaluated.

L. Witek, M. Wierzbin´ska and A. Poznan´ska [2] have done fracture analysis of compressor blade of a helicopter engine. From the visual examination of the fractured surface, it was possible to observe beach marks, typical of fatigue failure. The crack was initiated from the corrosion pit located on the attack edge of the blade. A non-linear finite element method was utilized to determine the stress state of the blade under rotation (operational conditions). In this analysis an undamaged blade was considered. Computations for the blade, working in the vibration conditions additionally were performed for analysis of phenomena occurring during the blade resonance. In this analysis first three mode of vibration were considered. Attention of this study is devoted to the mechanisms of damage of the compressor blade which works in the condition favourable for the pitting corrosion. In this study the numerical and experimental analysis were performed to investigate the damage mechanisms of the compressor blade of the small helicopter engine. The visual examination shows that failure was a typical fatigue fracture with beach marks. The corrosion pits were located both in the crack origin zone and also on the attack edge of blade near the rupture area. It was evident that corrosion pit was a main reason for the rapid crack initiation. Moreover if the helicopter was used in the maritime operations, the sea water environment caused acceleration of the crack growth and in consequence rapid damage of the blade. Results of the numerical stress analysis show which kind of load was more dangerous under fatigue damage process: rotation or vibration of the blade. By comparison results of visual inspection (shape of the beach marks) and FEA simulation (stress distribution) it seems that the crack initiation process can be accelerated bytorsional vibrations whereas meaningful influence on the rack growth process has the transverse vibrations of the blade. The general remark can also be formulated based on results of this analysis: the vibrations (high-cycle fatigue) are more dangerous than oscillated rotation (low-cycle fatigue) for compressor blade from the point of view of the fatigue strength.
Mokaberi, R. Derakhshandeh-Haghighi and Y. Abbaszadeh [3] have done fatigue fracture analysis of gas turbine compressor blades. Gas turbine compressor blades are subjected to centrifugal and vibratory loads. This repeated loading and unloading can reduce the life of the compressor

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blades. An experimental procedure has been done to investigate the fatigue crack propagation in blades. Microstructure and fracture surface of the blade have been investigated by optical and scanning electron microscopy. Fatigue crack propagation considering the effect of corrosive environment has been studied. Environmental and micro-structural features revealed that the catastrophic fracture was initiated from the corrosion pit on the leading edge of the blade. In this study the experimental analysis was performed to investigate the reason for early and sudden failure of compressor blades. Fatigue strength of compressor blade is greatly influenced by surface treatment which causes residual stresses and surface voids. On the other hand, working in sea-water environment leads to formation of corrosion pits on the blade surface which can be as stress concentration sites. Due to cyclic loading, cracks initiate from these sites and propagate as fatigue cracks in to the centre of the blade. SEM micrographs confirm the existence of corrosion pits and also the striations on the fracture surface. The decrease in blade life is because of these pits. In order to avoid early and sudden failure of blades, it seems rational to decrease the amount of corrosion by considering the humidity level and acidity of the environment. Washing of blades regularly and introducing anti-corrosion agents for compressor blades along with frequently obligatory inspections of the blades are recommended. Accurate inspections must be done for detecting non-uniform pressure distribution of gas or the loss of the blade material which may produce an unbalance on the rotor leading to overload on the blades.

Jianfu Hou, Bryon J. Wicks and Ross A. Antoniou [4] have done investigation of fatigue failures of turbine blades in a gas turbine engine by mechanical analysis. Blade failures in gas turbine engines often lead to loss of all downstream stages and can have a dramatic effect on the availability of the turbine engines. Thorough failure investigation is essential for the effective management of engine airworthiness. In this paper blade fatigue failures are investigated by mechanical analyses and by examination of failed blades. A series of mechanical analyses were performed to identify the possible causes of the failures by examining anomalies in the mechanical behaviour of the turbine blade. A non-linear finite element method was utilised to determine the steady-state stresses and dynamic characteristics of the turbine blade. The steady-state stresses and dynamic characteristics of the blade were evaluated and synthesised in order to identify the cause of blade failures. Due to the complex nature of blade failure, numerous aspects have to be examined. This paper has focused specifically on the possible causes of fatigue failure which may occur as a direct consequence of anomalies in the mechanical behaviour of the blade. In this study the likely cause of blade failure is considered to be a mixture of LCF and HCF as a consequence of blade tip/casing rub strap impact. The cause of such impact may be variation of the “as new” blade length and/or increases in blade length as a consequence of creep after an extended period in service. In both cases the risk of failure would clearly be exacerbated by poor material quality. The maximum stress in the blade under normal steady state conditions occurs at the top fir tree in the acute trailing corner, and that

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stress level is low. This indicates that centrifugal load, thermal expansion and gas pressure during steady state operation do not have a significant influence on crack initiation at the top fir tree in the acute leading corner, although they do determine the mean stress values. Gas dynamic fluctuation is an unlikely source of excitation as the frequency of the force would be well below the blade natural frequencies. No gas dynamic fluctuations appeared to match the blade natural frequencies. The pre-stressed modal analysis of the dynamic characteristics of the blade during service shows that the second vibration mode of the blade is most critical because the maximum stress corresponding to this mode is coincident with the point of crack initiation. The first bending mode, which is the one most easily excited is not associated with blade failure. V. Naga Bhushana Rao, I. N. Niranjan Kumar and K. Bala Prasad [5] studied failure analysis of gas turbine blades in a gas turbine engine used for marine Applications. High pressure temperature (HPT) turbine blade is the most important component of the gas turbine and failures in this turbine blade can have dramatic effect on the safety and performance of the gas turbine engine. This paper presents the failure analysis made on HPT turbine blades of 100 MW gas turbine used in marine applications. The gas turbine blade was made of Nickel based super alloys and was manufactured by investment casting method. The gas turbine blade under examination was operated at elevated temperatures in corrosive environmental attack such as oxidation, hot corrosion and sulphidation etc. The investigation on gas turbine blade included the activities like visual inspection, determination of material composition, microscopic examination and metallurgical analysis. Metallurgical examination reveals that there was no micro-structural damage due to blade operation at elevated temperatures. It indicates that the gas turbine was operated within the designed temperature conditions. It was observed that the blade might have suffered both corrosion (including HTHC & LTHC) and erosion. LTHC was prominent at the root of the blade while the regions near the tip of the blade were affected by the HTHC. It could be concluded that the turbine blade failure might be caused by multiple failure mechanisms such as hot corrosion, erosion and fatigue. Hot corrosion could have reduced the thickness of the blade material and thus weakened the blade. This reduction of the blade thickness decreases the fatigue strength which ultimately led to the failure of the turbine blade. The failure analysis was carried out on a 100 MW gas turbine engine used for marine applications. Its blades were made of Nickel based super alloy to sustain high temperature conditions and other corrosive environmental conditions. The micro-structural evaluation of the blade material at three different regions (root, mid span and tip) of the blade revealed that there was no micro structural damage took place due to operation of the blades at elevated temperatures, indicating that the turbine blades were operated in designed/normal operating temperature conditions. The turbine blades might have suffered due to both HTHC corrosion and LTHC corrosion apart from erosion. It was noticed that at the root of the blade, the surface was very rough and exhibited some colour change. It indicates the occurrence of the low temperature hot corrosion (LTHC) at this region of the blade. At the tip of the turbine blade, it was observed that there was loss of some material

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and reduction in thickness. This indicates that the blade tip might have been subjected to the combined mechanisms such as hot corrosion and fatigue. Some green coloration was also noticed at the tip of the turbine blade. It is a clear indication of the occurrence of high temperature hot corrosion (HTHC).

Rajni Dewangan, Jaishri Patel, Jaishri Dubey, Prakash Kumar Sen and Shailendra Kumar Bohidar [6] studied the stresses and deformations of a turbine were studied. The goal was to highlight the stress and deformation distribution to assist in the design of blades. The stresses and deformations developed as a result of the blade operating conditions at high rotational speeds and thermal gradients were evaluated using two types of heat transfer modes-conduction and convection, taking into consideration the material behaviour at elevated temperatures. The greatest stresses in the blades result from the thermal load caused by conduction, and they are located between the blades and disc. In addition an analytical method was used to evaluated and predict the stresses along the blades it gave a good estimate of the stress values compared to the finite element. It is important to design for as high temperatures gas as possible in order to attain a high thermal efficiency in gas turbines. In the case of power generating gas turbines, the increase of temperature leads to lower fuel consumption, reduced pollution and thus lower costs. The main reason for early and premature failure of the insert ring was due to severe service condition such as high temperature and oxidizing atmosphere of the combustion chamber near the burner that could be due to switching the gas fuel to gasoline or even inclination of the burner flam. The failure analysis was carried out on a 1 gas turbine engine Its blades were made of Nickel basedsuperalloy to sustain high temperature conditions and other corrosive environmental conditions. The micro-structural evaluation of the blade material at three different regions(root, midspan and tip) of the blade revealed that there was no micro structural damage took place due to operation of the blades at elevated temperatures, indicating that the turbine blades were operated in designed/normal operating temperature condition. Finally, it was concluded that the turbine blade failure of gas turbine used for marine application thickness decreased the fatigue strength of the blade which finally led to the failure of the turbine blades was caused by multiple failure mechanisms such hot corrosion erosion and fatigue. The hot corrosion reduced the thickness of the blade material and thus weakened the blade. Maria Cristina Cameretti and Raffaele Tuccillo [7] examined in this paper the response of a micro gas turbine (MGT) combustor when supplied with gaseous fuels from biomass treatment or solid waste pyrolysis or from an anaerobic digestion process. They have paid a special attention to a satisfactory compromise between the expectedCO_2reduction and the possible increases in pollutant emissions, like carbon and nitric monoxides. For serving this purpose, flameless regime was induced by either an external exhaust gas recirculation (EGR) or by an appropriate choice of the pilot injector location for exploiting a sort of internal EGR. They had analyzed combustion when low LHV fuel is supplied to MGT. Also a CFD simulation of combustor was done. The CFD simulation is carried out with advanced technique based on

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preliminary comparison of different oxidation mechanism and on the use of extended kinetic scheme coupled with probability density function (PDF)-flame let approach. Also a model for description of turbulent partially premixed combustion with RANS-CFD codes has been proposed. The authors evaluated the combustion model impact on the accuracy of result of numerical simulations of turbulent reactive flow by using two numerical codes i.e. the Sandia Flame implementing a 3D RANS integration of the Navier-Stokes equations using the EDM, and a 1D one, where the reaction of diffusion equations are numerically integrated only along the radial direction. Nithin Kumar K C1, Tushar Tandon2, Praveen Silori3, Amir Shaikh [8] has done Structural Design and Analysis of Gas Turbine Blade using CAE tools. In the analysis, it is observed that the bottom trailing edge of the blade section has higher stress value than the tip of the blade. The value of Von-Mises stress and deformation is obtained and it is seen that at 10000C, Alloy 685 and at 20000C, Ti 6242S exhibits least amount of stress and undergoes less deformation for a constant turbine speed of 10000 rpm with a pressure of 3.06 MPa. From this study it is observed that the bottom trailing edge of the blade is prone to failure. The top trailing edge of the blade exhibits large deformation as compared to overall blade. For the temperature range for 7500C-12500C, Alloy 685 is best suited and from temperature range of12500C-22000C, Ti6242S is suited and can be used. It is also found that with the use of thermal barrier coatings the above materials will exhibit greater stability and longer life.

Patil A.A and Shirsat U.M. [9] studied failure Analysis of Gas Turbine Blade. The failure of a second stage blade in a gas turbine was investigated by metallurgical and mechanical examinations of the failed blade. The blade was made of a nickel-base alloy Inconel 738LC. The turbine engine has been in service for about 73,500 hrs. Before the blade failure. Due to the blade failure, the turbine engine was damaged severely. The investigation was started with a thorough visual inspection of the turbine and the blades surfaces, followed by the fractography of the fracture surfaces, micro structural investigations, chemical analysis and hardness measurement. The observation showed that a serious pitting was occurred on the blade surfaces and there were evidences of fatigue marks in the fracture surface. The micro structural changes were not critical changes due to blade operation at high temperature. It was found that the crack initiated by the hot corrosion from the leading edge and propagated by fatigue and finally, as a result of the reduction in cross-section area, fracture was completed. An analytical calculation parallel to the finite element method was utilized to determine the static stresses due to huge centrifugal force. The dynamic characteristics of the turbine blade were evaluated by the finite element mode and harmonic analysis. Finally according to the log sheet records and by using a Campbell diagram there was a good agreement between the failure signs and FEM results which showed the broken blade has been resonated by the third vibration mode occasionally before the failure occurred. The fretting fatigue mechanism as the main cause of several premature failures of Ti6Al4V alloy compressor blades was characterized. No metallurgical and mechanical deviations were found for the blade material

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with respect to the standards. Instead, the fretting characteristics were distinguished in the fracture surfaces. The developed 2D numerical model clearly showed that stress concentration was occurred at the corner of EOC in the dovetail region. This directly implies that the cracking was responsible to blade stresses induced in service, and not a product of an isolated defect or anomaly within the component. The high level of stress at the contact surface can be due to the insufficient clearance between the blade root and the disk in the dovetail region. This stress concentration can initiate several cracks which eventually lead to the complete failure of the blade. Wassim Maktouf and Kacem Saï [10] have done an investigation of premature fatigue failures of gas turbine blade. A failure of a first stage compressor blade of a Gas Turbine Generator in a Gas Treatment plant caused severe mechanical damage to the compressor section and power supply troubles. In this paper, the blade failure is investigated by mechanical, metallographic and chemical analysis. A finite element analysis is performed on the blade geometry to identify the stress concentration areas and the stress/strain values. The investigation outcomes provided the most probable cause of the premature blade failure and the recommendations to mitigate such incidents. Based on the analysis, the failure of the 1st stage compressor blade from the subject GT occurred by a high-cycle fatigue (HCF) mechanism. The root cause of the failure was attributed to an internal metallurgical anomaly near the airfoil leading edge. Fatigue cracks initiated from the anomaly region and propagated towards airfoil mid-chord until final tensile overload separation occurred. Therefore, manufacturing process of the GT blades should be well monitored and controlled to avoid residual stresses or surface defects. Random checks on blades from each forging heat lot will reduce such risks. Operator should implement a rigorous on-condition monitoring of the GT rotor and spot any side bands close to the BPF excitation peaks. Load drop or transient regime of the turbines increases vibration amplitude when harmonic rotor frequencies are interacted with blade’s natural frequencies. Thus, the number of engine’s start-up and shutdown of the GT shall be reduced to the minimum. Routine baroscopic inspection of the GT rotor should focus on the stress concentration area of the blade located near the connection region of the airfoil and the root as shown by the FE analysis. The static loading analysis performed in this work needs to be completed by dynamic analysis to assess the blade resistance to fatigue induced by repeated/fluctuated loads and the aerodynamic cyclic stresses. Thermo-elastoplastic behaviour of the blade material is required for identifying the blade’s strain-life fatigue crack initiation and propagation. Tim J Carter [11] studied Common failures in gas turbine blades. Modern aviation gas turbine engines are considered to be highly reliable in that failures in service are rare. In fact this is a misconception, and freedom from service failures is largely the result of stringent standards imposed during frequent inspections. Most failures are thus detected at the incipient stage and appropriate action taken to prevent service failure. The common failures in gas turbine blades are mechanical damage, high temperature damage, high temperature exposure, creep failures, fatigue failures, corrosion failures.

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V. Vijaya Kumar1, R. Lalitha Narayana2, Ch. Srinivas [12] have done Design and Analysis of Gas Turbine Blade by Potential Flow Approach. The design features of the turbine segment of the gas turbine have been taken from the "preliminary design of a power turbine for maximization of an existing turbojet engine". It was observed that in the above design, after the rotor blades being designed they were analyzed only for the mechanical stresses. As the temperature has a significant effect on the overall stress in the rotor blades, a detailed study is carried out on the temperature effects to have a clear understanding of the combined mechanical and the thermal stresses. The first stage rotor blade of the gas turbine is analyzed for the mechanical axial and centrifugal forces. Knowing the fluid conditions at exit of the gas turbines, a value of static pressure was assumed at the turbine outlet. From this the corresponding enthalpy drop required in the power turbine is calculated. The peripheral speed of rotor and flows velocities is kept in the reasonable range so to minimize losses. In which the base profiles available and is analyzed later for flow conditions through any of the theoretical flow analysis methods such as "Potential flow Approach".
M.R. Jahangiri and M. Abedini [13] studied Effect of long time service exposure on microstructure and mechanical properties of gas turbine vanes made of IN939 alloy. In this study, the effects of long-term service exposure have been investigated on microstructure and mechanical properties of gas turbine vanes made of IN939 super alloy. The major micro structural changes for the investigated service-exposed vanes include the formation of continuous grain boundary carbides and the transformation (degeneration) of MC carbides located at the grain boundaries. The brittle σ phase, which is predicted to be stable on the basis of thermodynamic calculations, is not observed in the microstructure of service-exposed vanes. The micro structural changes during service lead to a loss in room temperature ductility as well as in creep properties of the alloy.

Swati Biswas, MD Ganeshachar, Jivan Kumar and VN Satish Kumar [14] have done Failure Analysis of a Compressor Blade of Gas Turbine Engine. The stage II compressor stator blade of a developmental gas turbine engine was found damaged during dismantling of the engine after test run. A portion of the blade was found fractured from the hub region at leading edge. A crack was also observed extending from the fractured surface towards the centre of the airfoil region of the blade. Low magnification stereo-binocular observation revealed presence of beach marks on the fractured surface indicating the blade failure in progressive mode. This observation was further confirmed by scanning electron microscopy. The crack origin was at the blade hub-stem junction on the leading edge side. Presence of machining/filing marks appeared to be the reason for the fatigue crack initiation from this region. No metallurgical abnormalities were present at the crack origin. However, deep filing/machining lines were observed at the stem region of the blade attributing to the cause of failure. The Compressor stator blade was found to have failed in progressive mode, i.e. by fatigue. The crack origin was at the blade hub-stem junction at the leading edge side. Presence of machining/filing marks appeared to be the reason for the fatigue crack initiation from this region. The machining/filing

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marks are to be avoided as they raise the local stress concentration level and can lead to fatigue failure. Therefore, sufficient care to be exercised to avoid usage of blades containing such notches / abrasion marks. Z. Mazur, A. Luna-Ramı´rez, J.A. Jua´rez-Islas and A. Campos-Amezcua [15] have done failure analysis of a gas turbine blade made of Inconel 738LC alloy. The failure analysis of the 70 MW gas turbine first stage blade made of nickel-base alloy Inconel 738LC is presented. The blades experience internal cooling hole cracks in different airfoil sections assisted by a coating and base alloy degradation due to operation at high temperature. A detailed analysis of all elements which had an influence on the failure initiation was carried out, namely: loss of aluminium from coating due to oxidation and coating phases changing; decreasing of alloy ductility and toughness due to carbides precipitation in grain boundaries; degradation of the alloy gamma prime (γ) phase (aging and coarsening); blade airfoil stress level; evidence of intergranular creep crack propagation. It was found that the coating/substrate crack initiation and propagation was driven by a mixed fatigue/creep mechanism. The coating degradation facilitates the crack initiation due to thermal fatigue. The substrate intergranular crack initiation and propagation were due to a creep mechanism which was facilitated by grain boundary brittleness caused by formation of a continuous film of carbides on grain boundaries, the degradation of γ due to elongation (rafting) and coalescence, and high thermo mechanical stress level.

S. Taamallah, K. Vogiatzaki, F.M. Alzahrani, E.M.A. Mokheimer, M.A. Habib and A.F. Ghoniem, [16] studied fuel flexibility, stability and emissions in premixed hydrogen-rich gas turbine combustion. There objective was to review the progress made in understanding the effects of fuel composition on premixed gas turbine combustion, with a special emphasis on system stability and emissions, for hydrogen-rich synthetic gas (syngas) mixtures. This is driven by the rising interest in the use of hydrogen blends and syngas in combined cycle power plants, as an alternative to standard natural gas. Typical applications where such mixtures are used include the recycling of hydrogen by-product from industry as well as promising pre-combustion carbon capture methods like fuel reforming or gasification integrated with gas turbine combined cycle plants. Syngas is mainly a mixture of H_2, CO and CH_4; its composition can vary due to fluctuations in the process's conditions but can also dramatically change if the feedstock is modified like coal or biomass grades in gasification. Due to the substantially different chemical, transport and thermal properties that distinguish the syngas components, especially H_2, when compared with conventional hydrocarbon fuels, these non-standard fuels pose several challenges in premixed combustion. These challenges are reviewed in this paper along with the combustion fundamentals of these fuels. A survey of available technologies able to handle syngas and hydrogen-rich fuel in general is provided reflecting the difficulties encountered while using these fuels in real large scale commercial applications. They find that a limited number of options exist today for fully premixed combustion, but promising designs are under development. Finally, the ever growing use of numerical simulation to cost-effectively study full scale combustion systems—with Large Eddy

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Simulations (LES) being at the forefront as a compromise between accuracy and computational cost—justifies the simultaneous review of the different numerical attempts to simulate hydrogen-containing fuel mixtures and syngas in premixed combustion. Challenges specific to performing LES calculations for these reacting flows are highlighted. We find that, while the literature on premixed LES methane combustion is abundant, LES of premixed syngas and hydrogen-rich fuels combustion is comparatively scarce. Munzer S.Y. Ebaid, Mahmoud Hammad and Talal Alghamdi, [17] had done thermo economic analysis OF PV and hydrogen gas turbine hybrid power plant of 100 MW power output. The design of a PV-hydrogen gas turbine hybrid power plant is proposed to generate100 MW electrical load. This electrical power is supplied directly from PV solar panels, and in the case of shortage or lack of solar radiation, it is supplied by a gas turbine power plant working on hydrogen fuel which is produced through using electrolysis of water by a PV generator. The hydrogen produced is stored directly in gas tanks under appropriate pressure. In the case of inability in supplying the load from PV generator, hydrogen fuel will be used through gas turbine. This study is examined in two cases; case (a): the design of the PV power plant based on worst case scenario; which corresponds to the minimum solar radiation and minimum sunshine hours during the year), and case (b): the design of the PV power plant based on average case scenario; which corresponds to the average solar radiation and average sunshine hours during the year. In both cases, the size of the gas turbine power plant and the size of the photovoltaic arrays required for operating day load, the number of water electrolysers, the capacity of hydrogen tanks required for storage purposes; all were calculated. The economic cost in each individual case was analysed taking into account, a profit of 25% of the initial cost. It was found that the price of the electricity produced is 0.12 $/kWh for worst case scenario, and 0.16 $/kWh for the average scenario. The payback period is 13 years and 15 years for the worst and the average scenarios respectively based on 8% interest rate.

Attila Kun-Balog and Krisztián Sztanko [18] studied the combustion characteristics of crude rapeseed oil. Their study was aimed at reduction of pollutant emissions from a rapeseed oil fired micro gas turbine burner. The experiments were performed on a burner test rig, which allowed to modify the factors affecting fuel atomization and to measure the emission of pollutants from a gas turbine burner equipped with an air blast atomizer selected for the purposes of the experiment. Measurement results confirmed that by preheating the rapeseed oil and performing the atomization using steam instead of air, the burner can easily be changed to burning crude rapeseed oil instead of diesel oil without increasing the emission of pollutants. The preliminary analysis showed that the viscosity and the surface tension of sufficiently preheated vegetable oils are similar to that of the diesel oil at room temperature. These are the dominant physical properties considering atomization, thus, preheating is usually indispensably necessary for vegetable oil firing. If the preheat is not enough to produce sufficiently fine spray, the increase of the gauge pressure of the atomizing fluid can improve the quality of the air blast atomization to the

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appropriate level. If the temperature of rapeseed oil is at least 80 °C and atomization takes place with superheated steam instead of air at gauge pressure of 0.95 bar, the emissions of unburned hydrocarbons and carbon monoxide are equal and the emission of nitric oxides is lower by 60%, than that of diesel oil firing with air blast atomization at the same gauge pressure. Xiuqin Zhang, Huiying Liu, Meng Ni and Jincan Chen [19] evaluated performance and parametric optimum design of a syngas molten carbonate fuel cell and gas turbine hybrid system. A novel model of the molten carbonate fuel cell (MCFC) and gas turbine (GT) hybrid system with direct internal reforming is established, where the fuel cell and the auxiliary burner are taken as the heat reservoirs of the gas turbine. Expressions for the power output and efficiency of the hybrid system are derived by considering various irreversible losses resulting from the over potentials in the MCFC, the heat leakage in the auxiliary burner, and the finite-rate heat transfer and compression, expansion, and regeneration processes in the gas turbine. The effects of some key parameters including the molar fraction of the oxygen in the oxidant, the utilization factor of the hydrogen in the MCFC on the performance of the hybrid system are revealed. It is found that the efficiency of the hybrid system will be increased by adding the utilization factor of the hydrogen, and the maximum power output of the hybrid system will be achieved when the utilization factor of the hydrogen is equal to 0.78. Moreover, the flowing rates of the syngas and oxidant and the molar fraction of the oxygen in the oxidant are determined under the optimal efficiency or maximum power output of the hybrid system.

Mukund H. Bade and Santanu Bandyopadhyay [20] analyzed gas turbine integrated cogeneration plant through process integration approach. A methodology is proposed to integrate gas turbine and regenerator with process plant directly at minimum fuel consumption. In addition to this, thermodynamic analysis of GTCP with regeneration is presented on gas turbine pressure ratio versus power to heat ratio diagram. On this novel diagram, limits of integration are identified and various regions of integration are presented such as infeasible integration, feasible integration, high stack, and no regenerator. Additionally, contour plots of energy utilization factors and fuel energy saving ratios are represented on this diagram for optimal integration of gas turbine with a process plant. It is interesting to note that though the contour plots of energy utilization factors and fuel energy saving ratios differ significantly, loci of the maximal energy utilization factor and the maximal fuel energy saving ratio are identical. It is noted that GTCP with regeneration is thermodynamically efficient at lower pressure ratios. The proposed analysis (maximum EUF and FESR plot on pressure ratio vs. R) can be used for retrofitting and grass roots design to select optimal configuration of GTCP. In grassroots design of GTCP, for a given R, optimal pressure ratio can be selected based on maximum EUF and FESR. The retrofitting case, for known pressure ratio, there are two values of R. Optimal R can be decided based on the objective of designer such as operating cost to be minimum or fuel energy savings (societal benefits) to be maximum. The shift of pinch point influences the sizing of GTCP. At very high R, GTCP plant behaves similar to gas turbine plant with regeneration.

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The maximum EUF and FESR are at maximum power plant efficiency with constant optimal pressure ratio for very high values of R (>Rl). The optimal pressure ratio for maximum power plant efficiency is lower than limiting pressure ratio at which specific net work is maximum. There may be trade off between gas turbine power plant efficiency, and its size and weight. Gas turbine power plant designed at optimal pressure for maximum power plant efficiency requires higher size and capacity due to lower specific net work. On the other hand, system designed for maximum specific net work requires high pressure ratio with heavy compressor and low power plant efficiency.

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