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Failure mechanisms in turbine blades of a gas turbine Engine –an overview

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Abstract:- For the past few decades, the gas turbines have been operated at elevated temperatures to have the advantage of achieving higher and higher power output and engine efficiency. The turbine blade is one of the most important components of the gas turbine and is principally made of Nickel base super alloys. Superalloys are metallic materials for service at high temperatures and the excellent thermal stability, tensile and fatigue strengths, resistance to creep and hot corrosion, and micro structural stability possessed by Nickel-base super alloys render the material an optimum choice for application in turbine blades. The main function of turbine blade is to translate thermal energy of gas at high temperature and high pressure into mechanical work. The gas turbine blades operate at very high temperature under conditions of extreme environmental attack and subjected to degradation by oxidation, corrosion and wear etc. Generally, during operation, the turbine blades are subjected to the failure mechanisms like Fatigue, Creep, Corrosion, Erosion and sulphidation etc. The failure of turbine blades may have severe impact on safety and reliability of the gas turbine engine. Keeping this in view, in this paper an attempt has been made to review the blade failure mechanisms and blade failures with some case studies.

Keywords:- Turbine blade, Failure mechanisms, Fatigue ,Creep, Hot corrosion, Erosion.

I. INTRODUCTION

Whether propelling aircraft through the sky, ships through the ocean or providing power to the electrical grid, gas turbine engines have become incorporated into our daily lives. As world moves towards a higher dependence on technology, there will be an increased demand for gas turbine engines to produce power with higher efficiencies. The turbine is responsible for extracting energy from the high temperature, high pressure gas produced by the combustor. Turbine blades were considered as the critical components of the gas turbine engines in which failures occur frequently. In some studies, it was reported that as many as 42 percent of the failure in gas turbine engines were only due to blading problems and thus the turbine blades are often the limiting component of gas turbines. In gas turbine engines, blade problems are of the utmost concern to designers and users. With the evolution of gas turbines toward higher turbine entry temperatures and pressure ratios, the problems of blades, especially in the hot section, have been accentuated.

The causes of blade failure are manifold. They include fatigue, creep, corrosion, erosion, sulphidation, foreign object damage (FOD) and vibration. In spite of the availability of sophisticated design tools, blade failures are prevalent in both compressors and turbines and it was reported that the components most commonly rejected are the blades from both the compressor and the turbine [1].

In this paper an attempt has been made to review the modes of failures in turbine blades of a gas turbine engine with some case studies which provides information to researchers, designers and users.

II. FATIGUE FAILURE

In most practical engineering situations especially the gas turbine blades, the applied stresses are not steady. Instead, the loading fluctuates, often in a random manner. Under conditions of cyclic stress, it is frequently found that failure occurs at lower stress levels than would be expected. This phenomenon is known as fatigue and it causes the majority of turbine blade failures while in-service.

The failure mode of fatigue is usually divided into the following 3 phases as shown in figure.1:
Crack initiation (Primary stage)
Crack propagation (secondary stage);
Unstable crack propagation (tertiary stage).

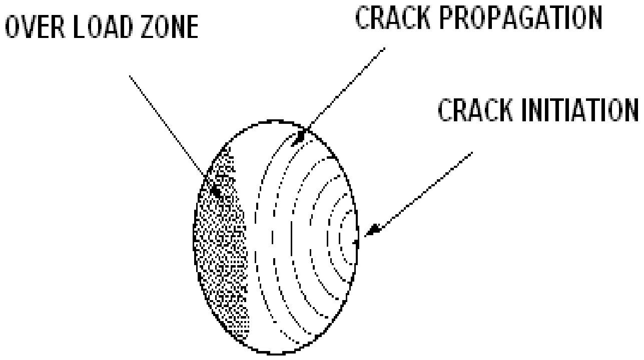

Figure.1: Phases of Fatigue Failures

Fatigue life of a gas turbine blade is dependent upon the choice of material and the magnitude of the cyclic stresses. Materials production and processing can also have a significant impact on life of blade in service. Micro-structural variables such as changes in grain size, alloying and the presence of non-metallic inclusions will affect the fatigue life. Fatigue behaviour is also very sensitive to the factors like Random stress fluctuations, Stress concentrations, Surface finish, Residual stresses and Corrosive environments etc [2]. The gas turbine blades principally made of Nickel-base superallloy. The excellent thermal stability, tensile and fatigue strengths, resistance to creep and hot corrosion, and micro structural stability possessed by nickel-base superallloy render the material an optimum choice for application in turbine blades [3–5]. These superallloy are the standard material for hot stages of gas turbines, where blades are subjected to high mechanical stresses, elevated temperatures and aggressive environments [6–20].

The design loads for gas turbine blades are mainly in the elastic region of the stress/strain curve of the material. The traditional approach to fatigue, for which the S-N curve was designed, chiefly concerned itself with failure after a large number of cycles. At higher stresses and lower cycles, the fatigue life reduces progressively and leads the failure of a component and the phenomenon is termed as Low Cycle Fatigue.

The transition point from low cycle fatigue (LCF) to high cycle fatigue (HCF) is generally assumed to occur where the total strain comprises equal proportions of elastic and plastic strain. However, for convenience, LCF is often considered to lead to failure in less than $l0^5$ cycles and HCF is lead to failure after more than 10^7 cycles. The intermediate range may be considered to fall into either region, depending on the design application. It must be remembered that it is not the number of times that a cyclic load is applied that is of particular importance. Rather the amount of damage accumulated during each application of the load. For critical gas-turbine components such as turbine blades, it is appropriate to differentiate between LCF and HCF by identifying the driver of the cyclic loading. LCF is typically driven by pilot demands and the application of relatively large loads whereas HCF is typically driven by sources of vibration and the application of relatively small loads [2].

2.1 Low cycle fatigue (LCF)

If the amplitude of the cyclic stresses applied to a component is very high (LCF), the accumulated strain energy per reversal will be significantly higher. For this reason, under LCF, a component will spend a very small proportion of its life in the primary stage, known as crack initiation stage and the majority of its life in the secondary stage known as crack propagation stage of fatigue failure. Most of the critical components within gas turbine engines, such as the turbine blades are subjected to very high loading cycles and are, therefore, life of those components are limited by LCF. The mechanical loading on these components is caused by the followings:

- Centrifugal forces and thermal loads
- High pressures within the casings, and
- Thermal gradients within components

2.1.1 Low cycle fatigue (LCF) in turbine blades

LCF is related to much higher stress cycles imposed by starting and stopping in engine operation. At rest, the turbine blades are subjected to loadings which are mainly due to their self weight and are normally at ambient temperature. In operation, the same turbine blades are subjected to large centrifugal forces which are imposed by the speed of rotation and blades are operated at much higher temperatures. The rate of change between the two states are rapid on engines and start rises the temperature difference and thus induces the high level of thermal stresses, reaches to steady state during operation and re-appear at the time stopping the engine operation i.e., during cool down. It was noticed that the life of the gas turbine blades used in gas turbine engines are affected largely by high transient loads (no of start-ups and slowing downs) to which the blades are subjected in service. However the degree of deterioration/failure of individual blades may differ due to several other factors. This rate varies considerably depending on the engine and is calculated mainly by the loadings imposed and also the temperature to which the turbine blades exposed during operation. For example, the life of a turbine blade used in small engine, at high speed and elevated temperatures might be limited to around 10,000 hrs or even less, while the life of a turbine blade in the same engine but at normal temperature and speed might be 20,000 hrs or even more. In some case studies it was estimated that the life of turbine blade used in engines for short journeys is as less as 5 years and where as in engines for long journeys, the life of turbine blade was appreciable and was up to the expectations.

The cyclic nature of these forces is due to variations in engine power setting. One complete or major cycle is experienced when the engine is accelerated from standstill to maximum engine rotational speed and then returned to standstill. Minor cycles of varying size are experienced for all other throttle movements. LCF for a gas turbine can therefore be characterized as loading cycles caused by variations in rotational speed, temperature distribution in parts, or engine internal pressure, which are most often due to throttle movement.

2.2 High cycle fatigue (HCF)

Fatigue failure occurs when either the material fracture toughness is exceeded by the combination of applied stress and crack size, or a critical crack size is attained in a highly stressed region of a component. The process to achieve either of these conditions involves crack initiation and sub-critical crack propagation. Whilst components under an LCF regime spend the majority of their lives in the crack propagation phase, for HCF, crack initiation often tends to be the time-consuming process. Low amplitude, high frequency loading cycles (HCF) could quickly propagate a LCF initiated crack to failure.

HCF is primarily a function of engine design. A component that fails in HCF does so because it has been subjected to a large number ($> 10^7$) of stress cycles. A number of factors can cause high frequency loading of components and are generally known as drivers.

2.3 Thermo-mechanical fatigue

Thermo mechanical fatigue damage is caused by a combination of the external loads and cyclic compressive and tensile loads induced by thermal gradients across components. This effect is particularly significant for turbine blades and especially cooled blades. Taking an uncooled HP turbine blade as an example, before first engine start it has no residual stresses and is at uniform temperature. Upon engine start the blade experiences high temperatures on its outer surface whilst taking longer to reach operating temperature at its core. This leads to excessive compressive forces particularly at the leading edge and the material plastically deforms to relieve the stress.

As the blade core reaches steady state temperature, the outer surface goes into tension due to the earlier compressive deformation. The centrifugal loading on the blade increases this tensile loading. As the throttle is retarded, the centrifugal forces reduce and the outer surface cools faster than the core causing the outer surface to contract. This contraction is opposed by the core, which holds the outer surface in tension. When the engine is shutdown and reaches the ambient temperature throughout, there remains a tensile stress in the outer surface of many components. This process enhances the level of tensile stress cycling experienced by the blade, particularly in the thinner sections such as the leading and trailing edges, where temperature changes occur most rapidly [2].

It can therefore be seen that the blade goes through a stress sequence with every change of temperature. The scale of the load imposed is proportional to the temperature gradient induced in the blade and this is a function of the rate of throttle movement. Therefore, for long engine life throttle movements should be made as slowly as possible. The thermal gradient will produce a stress field that varies across the radius due to the temperature differences and the coefficient of expansion.

Thermal fatigue is defined as the initiation and propagation of cracks in a material caused primarily by alternate heating and cooling. This heating and cooling almost always gives rise to a non uniform distribution of temperature which in turn causes cyclic thermal stress. This thermal stress of course leads to thermal-fatigue cracking. Thermal fatigue can (and quite often does) occur in gas and steam turbine blades, diesel engine pistons, railroad loco. The thermal-fatigue problem is of greatest concern to the engineers as it causes the initiation of cracks in aircraft gas turbine blades. Modern gas turbines are running at hotter and hotter temperatures in the search for increased efficiency, thrust, and economy. Service times are also being lengthened. These are the circumstances which tend to make thermal fatigue dominant as a mode of failure in the failure of turbine blades in gas turbine engines.

III. CREEP FAILURE

Creep is the tendency of a solid material to slowly move or deform permanently and occurs as a result of long term exposure to high levels of stress that are below the yield strength of the material. Creep is more severe in materials that are subjected to high temperatures for long periods, and near melting point. Creep always increases with temperature. Figure.2 shows three stages of creep.

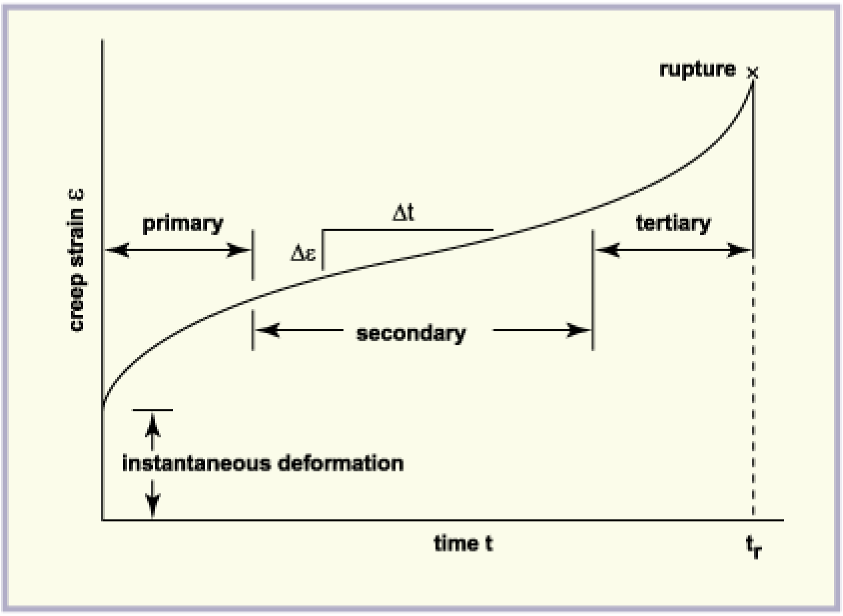

Figure.2: Three stages of creep phenomenon

The Primary Stage depicts rapid extension at a decreasing rate; this is of interest to the designer as it forms part of the total extension reached in a given time and so affects the choice of clearances. The Secondary Stage shows creep occurring at a relatively constant rate. This is the important part of the curve for most applications and it is recommended that the components which generally fail due to creep required to be operated in secondary stage. The Tertiary Stage shows an acceleration of the creep rate to failure. This stage should be avoided in operation and it is not easy to predict the transition from the Secondary Stage to the Tertiary stage.

The rate of this deformation (creep) is a function of many factors like the material properties, exposure time, exposure temperature and the applied structural load etc. Depending on the magnitude of the applied stress at elevated temperatures and its duration, the creep may become so large that a component can no longer perform its function. In a gas turbine engines the components which suffer most from creep are the turbine blades. Creep of a turbine blade will cause the blade to contact the casing, resulting in the failure of the blade. Creep deformation does not occur suddenly upon the application of stress. Instead, strain accumulates as a result of long-term stress. Creep is a "time-dependent" deformation. Creep affects hot section parts of turbine blades and the final stages of high pressure ratio compressors, and is predominant in the mid span region of the airfoil, which experiences the highest temperature. Creep strain is of interest because it leads to progressive reduction of rotor tip clearances. It can also occur in the disk rim region where high stresses and temperatures can cause time dependent plastic deformation.

3.1 Creep failure of gas turbine blade

The turbine blades especially HPT first stage blades normally considered the point of the highest temperature in the turbine portion [21]. Exhaust gases from the combustion chamber are directed into the turbine, impinge turbine blades airfoils, and specifically near the tips of turbine blades. It is understood that the clearance between the blade tips and the adjacent shrouds (casing) should be kept as minimum as possible to extract the maximum amount of energy from the hot stream of combustible gases from the nozzle. In general, creep is defined as blade stretch or deformation in which the blade elongates in operation at high temperature and stress. Creep of turbine blade during operation at high temperature, in abnormal conditions, makes the tips of the turbine blades to severely rub into the non-rotating shroud causing a ‘‘tip-rub’’ as shown in Figure.2. The rubbing often may adversely affect the blade tip, causing the engine to repair and sometimes may leads to the replacement of both blades and the non rotating shroud. In order to make the components free from such damages like creep, blades stretch is measured in frequent intervals and the extra length is trimmed to maintain the designed clearance between tip and the shroud. This has to be done to extract maximum amount of work from the gases at high temperatures and to avoid failure of the gas turbine blades due to creep as well [1]. The blades are removed/replaced when the strain accumulated reaches the predetermine value. To prevent the gas turbine blades from creep failures, it is important that the gas turbine engine is operated in normal limits of temperatures and the blades are inspected at frequent designed time intervals. Creep of turbine blades, sometimes causes the removal of coating from the tip region by contact turbine blade tip with the adjacent shroud. This causes the exposure of underlying super alloy material to oxidative and corrosive gases and this in turn may leads to failure of a turbine blade due to corrosion.

It is understood that under normal conditions, turbine blades should never be operated at excessive temperatures for long enough periods to cause micro structural damage. Some elevated temperature exposure is permitted for very limited periods, for example during start or for emergency situations. Such exposure should be strictly controlled, with inspection for possible damage, including metallographic examination of sample blades, being required. Once the microstructure has been degraded by exposure to elevated temperature, it is normally assumed that the blades have been damaged and replacement is mandatory. Exposure to creep can be detected by metallurgical tests, common indicators being the coarsening of the gamma prime precipitates and the formation of void cavities at grain boundaries. Details on creep may be found in Greenfield (1972). Often creep failures can be associated with a loss of cooling. This loss can be due to a quality control problem (such as blocked cooling passages) or due to a blockage or malfunction of the cooling airflow.

It is the point to be noted that the gas turbine blades are operated at elevated temperatures for a longer durations and hence it very crucial to understand the creep deformation behavior of a turbine blade material to eliminate failures due to creep mechanism.

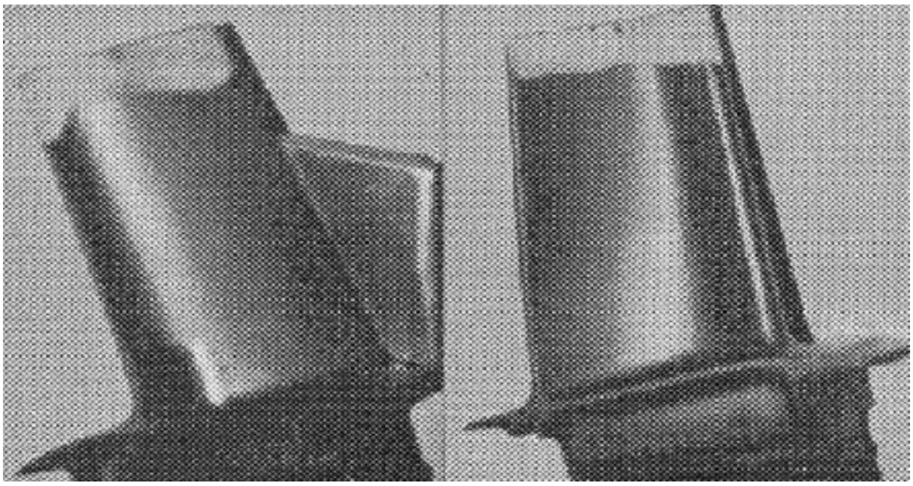

Figure.3: Cracks of the Turbine blade due to creep

IV. CORROSION FAILURE

The gas turbine blades are exposed to corrosive conditions and are operated at high temperature. The gas turbine engines facilitates to use wide range of fuels including heavy fuels and these fuels may contain the contaminants like sulphur, sodium, potassium, calcium, vanadium, lead, and molybdenum. This causes serious hot corrosion problems in gas turbine blades. Care must be taken to ensure that the fuel is properly treated to an acceptable quality prior to being introduced to the gas turbine engine. Fuel contamination with salt water is quite common when fuel is transported by barges and the airborne pollutants entering with the inlet air depend on the turbine location. Salt can also enter the gas turbine engine by means of the air. While this problem is very severe in marine gas turbine and the gas turbine plants located in coastal environments. Atmospheric contaminants from marine environments, pollution from industry, forest fires usually contains sulphur and sodium in the form of salts as active elements. These impurities in the air can lead to the deposition of alkali metal sulfates on the blade surfaces, resulting in the hot corrosion attack [22]. Some studies have shown that the turbine blades used in inland installation might also be affected by hot corrosion by airborne salt introduced into the gas turbine engine with air.

When the salt deposits on a surface of a blade already covered with a protective oxide, initially there is no reaction. But when the gas turbine engine is in operation, the damage mechanisms like erosion, thermal cycling etc., may sometimes cause the mechanical disruption of the oxide layer on the surface of the blade and thus may destroy the protective layer. This accelerates the oxidation and leads to the corrosion of turbine blade surface. In some cases, a local reducing environment may form due to incomplete burning of fuel. Such a reducing atmosphere also can damage the protective surface oxide layer.

4.1 Hot corrosion

Hot corrosion may be an accelerated damage phenomenon that occurs when high temperature turbine blades made of super alloys are operated in an environment containing salt and sulphur. The salt is derived from the air or enters the turbine via the fuel. Sulphur typically enters the turbine via the fuel. The basic reaction that occurs is represented by:

$$4NaC1 + 2SO_2 + 2H_20 + 0_2 \longrightarrow 2Na_2SO_4 + 4HCl \quad (1)$$

Hot corrosion of turbine blades can be intensified by the presence of vanadium, which produces V_20_5, which, in combination with the alkalis, can produce low melting point (approximately 600°C) vanadates, which while molten, can aggressively dissolve metal oxides. Sodium sulphate is a well-known corrosive agent that is formed in the flame from sodium chloride or other sodium compounds and sulphur containing organic compounds, which are present in almost any fuel [23]: In general, the rate of attack increases with increasing amount of contaminant [24].

There are two different types of hot corrosion forms have been reported, high temperature hot corrosion(HTHC) also known as type I and low temperature hot corrosion (LTHC) popularly known as type II. There are various parameters including alloy composition, gas composition and velocity, contaminant composition and temperature and temperature cycles, thermo mechanical and erosion processes [25] which may affect the development of these two forms. During reaction the sulphides are converted into complex unstable metal oxides and the sulphur thus released diffuses more deeply into the substrate where it forms more sulphides [26]. This leads to intergranular attack.

4.2 High temperature hot corrosion, type I

High temperature hot corrosion (HTHC) takes place at temperatures in 800^0C–950^0C range. The high temperature hot corrosion morphology is typically characterized by a thick, porous layer of oxides with the underlying alloy matrix depleted in chromium, followed by internal chromium-rich sulfides. It is generally believed that the molten sodium sulphate deposit is required to initiate hot corrosion attack. Type I hot corrosion generally proceeds in two stages: an incubation period exhibiting a low corrosion rate, followed by accelerated corrosion attack. The incubation period is related to the formation of a protective oxide scale. Initiation of accelerated corrosion attack is believed to be related to the breakdown of the protective oxide scale.

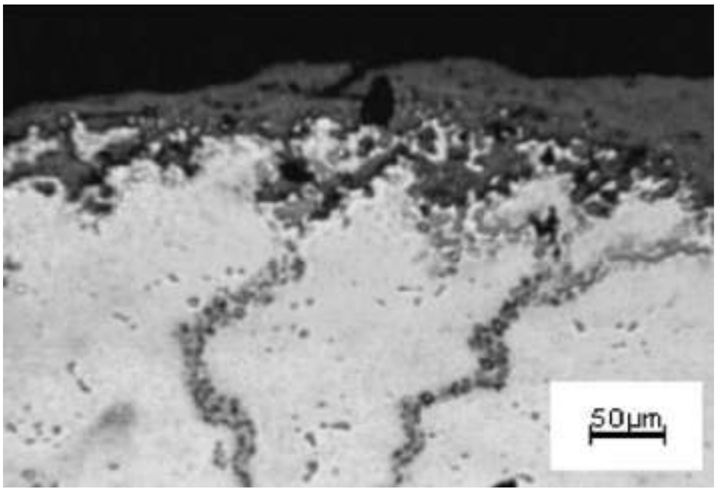

Figure.4: Type I hot corrosion, grain boundary diffusion and subscale sulfide particles are seen.

The high pressure side of the blade is a favourable location for the start of the type I reaction because sulphur rich gas entrained contaminant strikes this location first [26]. In another study it was confirmed that in most of the gas turbine blades, HTHC occurs away from the edges (i.e. middle of airfoil). With increasing height from the platform, the extent of this type of corrosion increased [27].

1.3 Low temperature hot corrosion, type II

Low temperature hot corrosion (LTHC) was recognized in the mid-1970s as a separate mechanism of corrosion attack. It takes place at temperatures in the 700°C to 800°C range and requires a significant partial pressure of SO_3. The extent of attack is related to the quantity of mixed salt present, which is stabilized by a high SO_3 pressure. The equilibrium Pso_3/Pso_2 ratio increases with decreasing temperature and high rates of corrosion can be observed at low temperatures. High rates of attack exhibiting the pitting morphology particularly for gas turbine components operating in a marine environment have been observed [28]. Low temperature hot corrosion characteristically shows no or little intergranular attack. LTHC (type II) is more aggressive at low temperature. As we know that the platform of the turbine blade is the low temperature region than the other regions and therefore these regions of turbine blades could be prone to type II hot corrosion attack [26]. It was reported that LTHC was concerned mainly to the trailing and leading edge regions. With increasing height from the platform, the extent of this type of corrosion decreased [27]. Generally in the regions near the blade tip, type I was evident (Figure.4). Type II was dominant close to the platform (Figure.5). Type II hot corrosion is rarely observed in aeroengines because the blades are generally operated at higher temperatures. However, marine and industrial gas turbines, which operate at lower temperatures, can experience low-temperature Type II hot corrosion. Increasing chromium in alloys or coatings will improve the resistance of the material to both Types I and Type II hot corrosion attack.

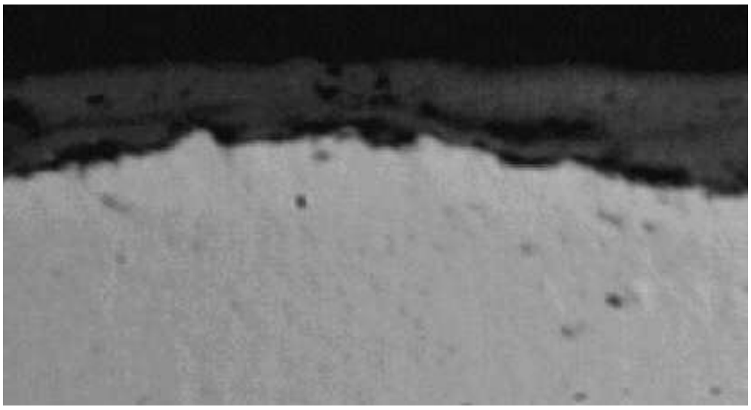

Figure.5: Type II hot corrosion, no grain boundary diffusion and subscale sulphide particles are seen.

Any of these corrosion forms may attack the Nickel based alloys from which turbine blades are made very readily at elevated temperatures. Corrosion causes loss of material, and can weaken a component of a gas turbine blade so much that it fails under normal loading. Corrosion can be controlled through careful selection of materials, the application of suitable coatings, and the maintenance of the surface finish throughout the life of the engine. It was noted that suitable coatings are to be applied to protect the blade material from the corrosion attack. Turbine blades are normally protected with sophisticated coatings, usually based on chromium and aluminium, but often containing exotic elements such as yttrium and platinum group metals to provide resistance to corrosion. However, if the engine is operated in a sufficiently contaminated environment, Attack is, inevitable either through atmospheric contamination or the presence of excessive quantities of harmful elements in the fuel. Corrosion is usually easy to detect during routine inspection. It is very difficult to detect a small corrosion pit that acts as a stress raiser hence causing a premature LCF or HCF failure.

4.4 Failure of turbine blade due to hot corrosion- a Case study

In one of the case study, it was reported that, the turbine blades made of Nickel base super alloys, used in industrial gas turbine of capacity 150 MW, were failed due to hot corrosion. The blade was operated for 5000 hours and with 110 starts and was tripped on high vibration. The blade material was uncoated and had suffered material loss, due to hot corrosion, resulted in the weakening of the turbine blade. A study was made on hot gas path deposits shows the presence of salt and its concentration levels were around 0.1 mg/cm^2, which is sufficient to cause hot corrosion.

V. EROSION FAILURE

Erosion is the abrasive removal of material from the flow path by hard particles impinging on flow surfaces. These particles typically have to be larger than 20µm in diameter to cause erosion by impact. This mechanism rarely cause catastrophic failure in turbine blade, but contribute to other failure modes and can be of considerable economic significance. Erosion can occur in blades of both compressor and turbine of a gas turbine engine and is probably more a problem for aero engine applications, because state of the art filtration systems used for industrial applications will typically eliminate the bulk of the larger particles. In gas turbine engine, damage to the surface of the turbine blade is often caused by large foreign objects striking the surface of the blade material. These objects may enter the engine with the inlet air, or the gas compressor with the gas stream, or are the result of broken off pieces of the engine itself [29]. Erosion is an uncommon source of mechanical damage caused due to carbon particles. These particles are deposited as coke around the fuel injection nozzles when the spray pattern of the nozzle is degraded, passing through the turbine. Similarly, particles of ceramic thermal barrier coatings which are applied to the surfaces of the combustion chamber to assist with keeping the walls cool, detaching due to thermal shock and passing through the downstream blades of the turbine and thus causes erosion of the surface of blades [1].

Apart from particulate erosion, there also exists the important phenomenon of hot gas erosion. Modern air cooled gas turbine blades operate at metal temperatures, lower than the gas path temperatures. The blade material surface is protected by means of the natural boundary layer or by a cooling air film. If this cooling layer of air breaks down even for short periods of time, or cooling effectiveness drops, then the surface asperities (roughness) of the blade contacted by the hot gas are subjected to high thermal stress cycles. After several cycles, damage takes place and the increased roughness (erosion) worsens the problem and finally may lead to decreased performance and the failure of turbine blade.

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5.1 Failure of turbine blade due to Erosion- a Case study

This case relates to a gas turbine plant with a capacity of 150 MW and the turbine was operated for about 1860 hours during a period of 3-year time, with 65 times started up. The plant is located a short distance from the sea. It was observed that some of the stationary and moving blades were get damaged by solid objects and particles, which might be originated from the destroyed blades of the 1st row. After inspection of the blades, it was observed a deep damage on its surface, caused by foreign bodies, probably coming from the deteriorated moving blades of the first stage, located upstream. Figure.6 illustrates the diaphragms of the second turbine stage of gas turbine engine.

Figure.6: Erosion of gas turbine blade

This shows that the surfaces of the diaphragm blades present severe damage, caused by foreign bodies (solid particles). It was found that the damages of blades of subsequent stages were caused as a result of disintegrated materials coming from moving blades of the first stage. It is argued that some of these blades might first get fractured damaging subsequent blades of the turbine gas Path. Analyzing the results of the visual inspection, it could be concluded that the moving blades of the first stage fractured first and damage the blades of the later stages. Other damages were a direct consequence of the disintegration into small fragile particles of the first stage moving blades. That disintegration caused a stream of small foreign bodies and solid particles, which eroded some surfaces of the turbine blades [30].

VI. COMBINATION OF FAILURE MECHANISMS

Blade failures in gas turbine engines might be caused due to the damage mechanisms like fatigue, creep, corrosion, erosion, sulphidation, foreign object damage, and vibration. However in many cases, blade failures are caused due to combined failure modes/mechanisms. For example, Corrosion of turbine blades can reduce blade thickness and decreases the fatigue strength of the blade material and thus finally leads to the failure of the turbine blade. Foreign object damage can cause nicks and cracks in turbine blade that can then be propagated either by low or high cycle fatigue and causes the failure of blade material. Fretting wear in the blade attachment regions can reduce damping, causing increased vibration amplitudes and alternating stresses. Apart from these mechanisms, failure analysis of gas turbine blades must investigate all engineering causes including design issues, environmental factors, cleanliness of the fuel, air quality, material, and gas turbine operating and maintenance history.

Consequently, failure analysis of gas turbine blades must investigate all engineering causes including design issues, environmental factors, cleanliness of the fuel, air quality, material, and gas turbine operating and maintenance history.

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