Failure analysis of a gas turbine blade: A review

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Abstract. Blade is an essential component of a gas turbine that functions to convert thermal gas energy at a high temperature and pressure into mechanical energy. Gas in the turbine blade works at a high temperature and pressure. High temperatures and pressures cause turbine blades to be one part of turbine components that often fails. Failure of the blade results in performance and turbine efficiency. The cause of failure on the blade is influenced by several factors, including fatigue, creep, oxidation, degradation of the coating on the turbine blade, corrosion, erosion, and surface degradation due to working at high temperatures. The hot temperature on the blades work on turbines around 1927 F to 3500 F and is one of the main factors in the failure rate. Individual blade failure rates differ due to operating temperature, rotation speed, operating mode, total service time, and differences in fabrication. This article discusses several case studies of failure in turbine hot section components such as blades to support the failure investigation is the key to improving turbine efficiency.

Keywords: failure, turbin blade, ductile, brittle

1. Introduction

Gas turbines convert thermal energy obtained from the combustion of fuel in pressure gas and high temperatures into mechanical energy to drive electric generators (1). The engine of a gas turbine consists of three main parts, namely compressor, combustion system, and turbine (2). Components in the combustion system have a significant role in ensuring reliable operation in various air/fuel ratios and loads.

Conditions of hot section components such as nozzles, burners, and blades exposed to hot gas coming out of the combustion system are very vulnerable to failure (3). The first stage blades in the turbine are considered very critical in hot gas path inspection. The most common failure mechanism modes in the nozzle and blade are fatigue, creep, erosion, and corrosion (1,4). The first stage blade in a gas turbine functions as a guide of hot gas supplied from the combustion chamber towards the turbine blade so that the blade experiences high heat pressure (5). Blades in turbines are usually made of nickel superalloys, coated with a thermal barrier (6).

Turbine blades are one of the main components of gas turbines that, during the operation, experience high temperatures. High temperatures on the turbine blade are around 1927 F to 3500 F.
F. This condition can cause degradation of the blade so that it can ultimately reduce the service life and failure of the turbine (Figure 1) (3). The failure mechanism on the turbine blade occurs due to several factors with different conditions such as creep, fatigue, oxidation erosion, and corrosion (2,7,8). Several factors causing turbine failure are interrelated and can occur simultaneously; for example, a crack can occur by the mechanism of creep or fatigue (6). Creeps can significantly reduce fatigue strength and cause failure in the turbine component. Failure in the turbine blade causes the power to die, potentially leading to prolonged outages and economic losses. When failures occur, it is necessary to carry out a detailed failure analysis on the turbine blade to understand the problem and improve the reliability of the turbine system.

Turbine blades are made of nickel and cobalt superalloys because they can withstand high pressure and temperature. Nickel superalloys have exceptional mechanical properties such as strength, toughness at high temperatures (650°C - 1100°C), and resistance to degradation in corrosive or oxidizing environments (1). One type of superalloy nickel that is often used on turbine blades is IN738. IN738 has multifunctional microstructure and strength at high temperatures from the intermetallic precipitate and phase compounds (Ni3Al) (2). The type of MC carbide phase was deposited during alloy solidification. In contrast, the M23C6 precipitate in the alloy was mostly deposited from the matrix along the grain boundary during heat treatment and blade operation at high temperatures (at 760-980 °C) (4).

Microstructure influences tensile and creeps strength properties. The change in morphological phases deposited as carbide, mainly, is one of the damage mechanisms that lead to the degradation of microstructure and reduction of mechanical properties. This paper aims to unveil the efforts made in reviewing the mode of failure mechanism of the blade of a gas turbine engine with several case studies that provide information to researchers, designers, and users.

2. Factors influencing gas turbine blade failure

Most gas turbine failures occur in hot section components, such as nozzles and blades (3). Blade failure is characterized by surface damage such as cracks and creeps during overhaaoul investigations. Other indications of failure are fatigue, wear, and corrosion (9,10).

![Figure 1. Failure on the gas turbine blade (5,8)](image)

2.1. Fatigue failure

Turbine blades experience repeated loading during operation due to the large centrifugal force caused by high rotational speed and temperature (11). The rate of change between conditions of rotational speed and high temperatures is expedited on the engine resulting in a high level of
thermal pressure distribution (9,12). Repeated loading causes the blade to experience fatigue. Blade fatigue depends on the nature of the cycle due to variations in turbine engine settings. A complete cycle of fatigue loading on the turbine is experienced when the engine accelerates from stopping to maximum engine rotation speed and then stops again. A small cycle of fatigue loading on the turbine results from the throttle movement (13).

Lower cycles and higher pressures result in fatigue life being progressively reduced, leading to failure of components. This phenomenon is called low cycle fatigue (LCF), while the low amplitude and high frequency are called high cycle fatigue (HCF) (14). LCF fails under the cycle $10^5$ while HCF fails above the cycle $10^7$ (9).

The life of a gas turbine blade is largely affected by high transient loads (no start-up and retarding) where the blade is used (15).

The engine start-up process, the blade will experience high temperatures on the outer surface and take longer to reach operating temperatures on the blade core (9,16). This process causes excessive compressive force, especially at the forefront, and the material undergoes plastic deformation to remove pressure (17).

However, the level of damage/failure of individual blades may differ due to several other factors. This rate varies greatly depending on engine, load, and blade temperature during operation. For example, turbine blades used on small turbine engines, at high speeds and high temperatures may have a lifetime of around 10,000 hours or even less, while turbine blades on the same engine but at a normal temperature and speed may have a lifetime of more than 20,000 hours (9).

Material failure occurs if the fracture toughness of the material is less than the stress intensity factor caused by the applied stress combination and crack size (18). The process of fatigue failure begins with crack initiation, crack propagation, and final fracture (19). Phase initiation and crack propagation are more dominant in LCF conditions, whereas in HCF, it takes a long time in crack initiation (Figure 2).

2.2 Thermomechanical fatigue failure (TMF)

Thermomechanical fatigue damage is caused by a combination of external loads, compressive load cycles, and tensile loads due to thermal gradients across all components (6,14). This effect is very significant on turbine blades, especially on cooled turbine blades. Turbine blades that are not cooled, before the first engine is started, have no residual stress and is at the same temperature.

![Figure 2. (a) Crack Initiation and (b) Cracks Propagation](1)

Wang et al. (2020) investigated thermomechanical fatigue experiments on blades with NickL Aloy material. The analysis showed that the initiation of cracks on the blade began at the end of the trailing and propagated along the leading edge. Besides, the fracture analysis indicated that there are multiple sources of cracks on the surface of the test section, and holes that are
susceptible to stress concentrations are found on the surface of the turbine blade. Deep holes are one of the causes of crack initiation. Therefore surface quality has an essential impact on TMF damage from turbine blades.

Figure 3. Thermomechanical Fatigue Testing (6)

The TMF crack surface is dark because of oxidation, and almost all crack surface is covered by an oxidation layer (20). Oxidation plays an essential role during the initiation and propagation of TMF cracks. In addition, transgranular fractures (typical features of fatigue damage) and intergranular fractures (typical features of creep damage) were observed on crack surfaces resulting from TMF testing (Figure 4) (14,21).

The blade experiences a voltage with each temperature change gradient. The temperature change gradient induced on the blade is proportional to the load applied to the blade. This relies on the movement of the throttle. The throttle must be made as slow as possible for long engine use (9). Oxidation plays an essential role during initiation, and a river pattern characterizes the propagation of thermomechanical fatigue cracks. River pattern is a sign of transgranular fracture, one of the typical features of fatigue damage (22).

Heating and cooling processes of the turbine blade cause a non-uniform temperature distribution that will create a thermal pressure cycle. The thermal pressure cycle on the turbine blade causes the blade to experience thermal fatigue (16). Thermal fatigue is defined by crack initiation and crack propagation. Modern gas turbines operate at hotter and hotter temperatures in search of increased efficiency, thrust, and economy. The usage time is also extended, which tends to make thermal fatigue more dominant as the turbine blade failure mode (23).

2.3 Creep failure
Creep is a tendency for solid material to slowly move or permanently deform as a result of long-term exposure to high-stress levels that are below the yield strength of the material (24). Creep is more severe in materials that have been experiencing high temperatures for a long time, and are approaching the yield point so that they can fail. Creep failure can be seen from morphological observations, namely the appearance of intergranular cracks due to the influence of high temperatures (6).

Turbine blades, especially the first stage blade, are the components that are most commonly affected by creeps. The creep rate of the blade depends on material properties, exposure time, exposure temperature, and applied structural load (1,25). Creep causes the blade to come into contact with the shell, which will cause turbine blade failure (19). Failures occur as a result of severe blade movements rubbing against a shell that is not spinning and causing tip rupture (9). In avoiding this failure, the distance between the blade tip and the adjacent shell (shell) must be kept to a minimum to extract the maximum amount of energy from the flammable gas heat flow from the nozzle. Creep on the blade also results in the loss of the coating layer at the edge of the blade.
adjacent to the shell (8). These conditions can cause the superalloy blade material to become oxidative and corrosion. Heat oxidation factors include high temperature, fuel and air contamination, and thermal pressure caused by the working conditions of the blade (11).

![Figure 4. a) Crack initiation and river pattern, b) Intergranular fracture (6)](image)

Turbines must not operate at excessive temperatures for very long periods, causing changes in the microstructure. Microstructures that have been damaged by exposure to high temperatures can be assumed that the blade has been damaged, and blade replacement must be done. Indications for creep can be seen through metallographic observations in the presence of hardening of the prime gamma (γ’) and the formation of cavities at grain boundaries (2). Creep can also be associated with a blade that is not cooled due to several factors such as blocked airflow in the cooler.

Kolagar et al. (2017) explored the failure analysis at the first stage turbine blade. The results showed that the prime gamma microstructure γ’ and secondary, MC, and M23C6 are distributed continuously through grain boundaries. Morphology of the depositional phase γ’ is one of the damage mechanisms that lead to the degradation of the microstructure and the reduction in mechanical properties of the turbine blade.

2.4 Corrosion failure

Gas turbines use a variety of fuels, including heavy and light fuels, which contain chemical elements such as sulfur, sodium, calcium, vanadium, lead, and molybdenum (26). The fuel can be a serious problem of heat corrosion on the blade if it is contaminated with saltwater when the fuel is moved into the turbine from the barge with air pollutants. Atmospheric contamination from fuels containing dominant sulfur and sodium and industrial pollution can cause impurities in the active element (3). This impurity in the air can cause the deposition of alkali sulfate metal on the blade surface, which results in a heat corrosion attack (5). Several studies have reported that turbine blades used in land installations may also be affected by heat corrosion by air salts that are fed into gas turbine engines with air.

Impurity attached to the blade surface that has been coated by a protective oxide initially does not react, but with the presence of a gas turbine engine operating a mechanism of corrosion, erosion and thermal failure can occur. The failure process can occur because impurities that have accumulated on the blade cause the protective oxide layer on the blade surface to be damaged or lost so that it can accelerate oxidation and corrosion on the turbine blade surface (11).

Hot corrosion in turbines is divided into two parts, namely high temperature and low-temperature solids. High-temperature corrosion occurs in the temperature range of 800 °C - 900°C which is characterized in morphology as thick and porous oxides with alloy matrices that are
essentially drained in chromium (4). Hot corrosion occurs in two stages, namely in the incubation period, starting with a low corrosion rate and followed by a rapid corrosion attack, causing damage to the oxide protective layer (20).

Figure 5. a) Micro carbide structure dam, b) Pitting Corrosion [1]

High pressure and temperature on the blade trigger the occurrence of heat corrosion at high temperatures due to the contamination of gases containing dominant sulfur to enter and attack the blade first. The blade has a lot of damage in the far part of the edge, namely in the (middle of the airfoil) (8).

Low-temperature heat corrosion occurs in the temperature range of 700°C - 800°C and requires partial pressure of SiO3. High corrosion rates can be observed at low blade temperatures, as indicated by the presence of pitting morphology (7). Pitting morphology usually occurs on the blade platform on the part affected by low temperatures. Marine and industrial gas turbines (Figure 5), which operate at lower temperatures, can experience low-temperature heat corrosion. Increased chromium in alloys or coatings will increase material resistance to high-temperature and low-temperature heat corrosion attacks.

2.5 Erosion failure
Erosion occurs due to erosion of abrasive material by hard particles that hit the flow surface. Particles must be larger than 20μm in diameter to cause impact erosion. Large particles enter the turbine through various media such as air, gas flow, or pieces of broken engine components, which then attack the blade surface and fail (Asadikouhanjani et al., 2014).

Erosion is an unusual source of mechanical damage caused by carbon particles. The causes of erosion failure from the blade can occur various factors, such as a layer of ceramic particles that serves as a thermal barrier in the combustion chamber to keep the temperature cool, these ceramic particles can be released due to thermal shock and pass downstream of the turbine (Moussavi Torshizi et al., 2009). After passing downstream of the turbine, the broken ceramic material attacks the blade so that it can cause failure (Figure 6).

The blade surface is protected by a cooling air layer if the cooling layer is damaged even for a short time, or the effectiveness of the heating and cooling processes decreases. The rough blade surface that is in contact with hot gas will experience a high thermal stress cycle. After a few cycles, damage occurs, and an increase in roughness (erosion) exacerbates the problem. It can ultimately cause a decrease in performance and failure of the turbine blade (Rani et al., 2019).
3. **Blade failure precautions**

Recommendations to increase blade resistance to failure are offered

- Using a suitable coating on the blade to increase thermal, erosion and corrosion resistance (Mirhosseini et al., 2020; Sushila Rani et al., 2017)
- Using filtration suitable for fuel and intake air intakes (Mirhosseini et al., 2020)
- Method of repairing the blade (overhaul) after recommended use in the manual book blade (Pelaseyed et al., 2019)
- Placement of friction absorbers between the bladed disk (Mirhosseini et al., 2020)
- The distance between the tip of the blade and the adjacent shell (shell) must be kept to a minimum to extract the maximum amount of energy from the heat flow of combustible gas from the nozzle (Rao et al., 2020)

4. **Summary**

Blade damage to the gas turbine engine occurs due to several factors, including fatigue, creep, corrosion, erosion, and damage due to foreign objects that enter and accumulate on the blade. The blade experiences repeated loading during operation due to the result of the centrifugal force generated by the rotational speed and high temperature. Centrifugal force acting on the blade causes the blade to experience fatigue failure. Fatigue failure on the blade can also occur due to the entry of foreign objects/damage to the turbine component in the turbine and attacking the blade so that it can cause crack initiation, which is then propagated by low cycle (LCF)/high cycles.

Failure of creep in the blade, especially in the first stage blade occurs due to exposure to high temperatures for a long time and approaching the yield point. The creep rate of the blade depends on material properties, exposure time, exposure temperature, and applied structural load. Creep causes the blade to come into contact with the shell, which will cause turbine blade failure. The distance between the blade tip and the adjacent shell (shell) must be kept to a minimum to extract the maximum amount of energy from the heat flow of combustible gas from the nozzle in preventing failure. Corrosion of turbine blades occurs due to the contamination of dominant fuels containing sulfur, sodium, and industrial pollution, which become impurities of the active element. The impurity that has accumulated on the blade causes the protective oxide layer on the blade surface to be damaged or lost so that it can accelerate oxidation and corrosion on the turbine blade surface. Corrosion can reduce the thickness and reduce the fatigue strength of blade material and ultimately result in turbine blade failure.
Further analyses of gas turbine blade failure are encouraged to investigate all technical causes, including design factors, environmental factors, fuel cleanliness, air quality, materials, and history of operation and maintenance of gas turbines.

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