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Brief survey on mechanical failure and preventive mechanism of turbine blades

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A B S T R A C T

Failure of components is one of the serious concerns especially in case of turbines. A comprehensive review is conducted in view of failure mechanism especially of the turbine blades. Further, various tools and techniques used in the analysis and investigation of failure mechanism are delineated in the present work. A summary of prevention of failure mechanism in various categories of turbines is presented as well. Moreover, turbines especially the gas turbine, steam turbine, hydro turbines, wind turbine etc. which are extensively used in the generation of power are considered for the investigation of failure mechanism in the current review approach. Results revealed that there are various types of failures such as crack, fatigue, corrosion, erosion, material defect, thermo-mechanical failure etc. which commonly occur at turbine blades and hub. The failures in the gas turbine include the crack, corrosion, fatigue failure etc. whereas in hydro turbines erosion and fatigue occur mainly. Consequently, the present work can be referred as a guide for failure mechanism and their prevention in the turbines.

1. Introduction

Turbines are the work producing devices. There are various modes of operating the turbines based on hydraulic energy, steam, gas, wind etc. [1]. Failure of the turbines is one of the major concerns. Under the operating conditions, there are various failures that can occur like blade failure, hub failure [2-5], bearing problems [6] etc. Blades play an vital role in the working of a turbine. Fluid impinges and causes the rotation of the hub which in return produces the mechanical power and that can be further utilized for various applications [7]. Blades are generally made up of alloy steels so that they can withstand the force applied by the fluid. The failure of blades is one of the serious and recurring problems while dealing with the turbines. A blade can be said to be failed if it is not able to perform its intended function throughout its service time. Broadly the failure of the turbine can be classified as crack failure, fatigue failure, corrosion, erosion etc. [8]. Crack failure can be any hairline fracture on the foremost or the straggling edge of the turbine. Fatigue failure may be because of the fluctuating loading on the blade which may results in exceeding the stress beyond the yield limit. Corrosion can weaken the blade due to the creation of oxides. Erosion of the blade is due to the pitting action on the blade by the various silica particles present in the fluid. Therefore, the blades used in the thermal power plants, hydro turbines, wind turbines etc. must be resistant enough so as to fulfill a certain service time or life time.

To study the failure of the turbine blades various techniques which can be used are X-ray diffraction technique [9,10] which helps in determining the metallurgical arrangement of the blade material. Scanning electron microscope [11] can be used for the study of the cracks and their propagation. Nowadays, computational fluid dynamics (CFD) one of the numerical techniques is widely used for the study of the pressure distribution on the blade which helps in determining the critical section that may leads to failure [11]. Finite element method can be used for determining

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the stress values, deflections, elongation etc. [12]. In literature, researchers have investigated the failure mechanisms of the turbine blades and suggested some preventive measures which are discussed below in the following sections.

2. Failure mechanism of turbines blade

A turbine blade is said to be failed if it is not able to serve its service intended purpose i.e., the working hours of the turbine blades are less than the expected life-time. There are different failure mechanisms in different types of the turbine. Mainly the failure mechanisms depend on the working fluid, unwanted foreign particles (like rock, silica), blade material strength, working conditions etc. Different failure mechanisms in various turbines are discussed below:

2.1. Failure mechanism of gas turbine blade

Rani et al. [13], studied different reasons which cause the failure at the first stage of the gas turbine blade. The blades are made of super alloy IN738LC which is nickel based and contain aluminide coating. In their study, authors examined the tip crack at trailing edge. Authors used visual observations, energy dispersion spectroscopy (EDS), scanning electron microscope (SEM), and material composition analysis. It was observed that corrosion pits were formed on the blade surface that acted as a notch and produced concentration of stress. The degraded surface of gas turbine blades failed due to excessive heat, hot oxidation and oxidation. Finally, with the use of optical emission analyser spectrometer authors concluded that blade did not fail due to the material defect but due to the pits of corrosion. The surface degradation took place because of the oxidation of Pt-Al2 coating. In order to prevent the failure in the first stage gas turbine blade authors suggested to select the best corrosive resistant material. Fig. 1 presents the inner view of a gas turbine, while the damaged leading and trailing ends are given in Fig. 2.

Khan et al. [14] examined the intergranular corrosion in second stage gas turbine blade. The intergranular corrosion has been considered very decisive for the life of the blade. In their study, the blade was made of super alloy Udimet 500, based on nickel. The high heat exposure and the alkaline media exposure were introduced for finding the failure results. Study showed that chromium carbide (CC) advanced at the grain boundaries while exposure to

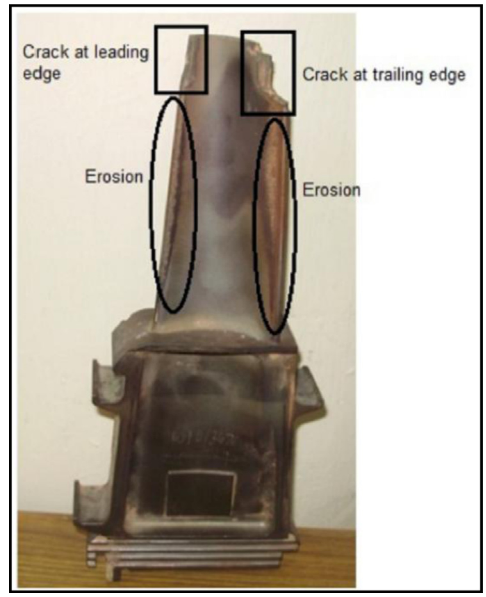


Fig. 2. Crack and Erosion on the leading and trailing edge [13].

900 °C and huge CC leaded at the corner while the surface face high temperature as 950 °C because of intergranular corrosion. Pitting was found on the grains and also at the grain boundaries of the blade specimen on exposure to alkaline media. Due to these pits stress was concentrated and the intergranular crack initiated. Later on propagation of this crack resulted in the blade failure. In order to control this failure temperature control was suggested by using thermal barrier coatings.

Camacho et al. [15] studied a gas turbine's blade subjected to wear damage. The techniques used were energy dispersive X-ray analysis, atomic force microscopy (AFM) for blade roughness determination, hardness test, and SEM for wear mechanism identification. The modes of the wear were found severe pitting action, corrosion, few irregular scratches and large craters similar to erosion. The turbine blade was made of high strength stainless steel having composition like Cr, Ni, Fe and C. the higher values of the degradation of the surface were reached in low pressure side of the blade. Similarly, Maktouf et al. [16] investigated the inability of the gas turbine generator first-stage compressor blade at gas treatment plant (Fig. 3). Finite element method (FEM) analysis

Fig. 1. (1) Internal view of 30 MW gas turbine. (2) First stage gas turbine blade [13].

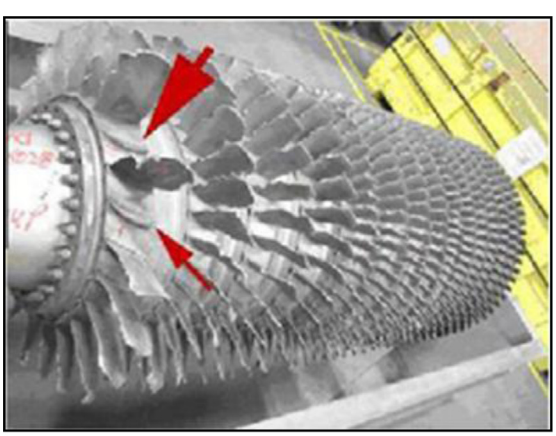
was performed to observe the stress concentration and stress strain values other than this some mechanical, metallography and chemical analysis were done. The material used was UNS N07718 complying with ASTM B637. Visual inspection, stereomicroscopy, metallography, fluorescent penetrate inspection (FPI), SEM, EDS, and hardness testing were done to study the failure. After the analysis it was observed that the first stage compressor blade failed due to high cycle fatigue mechanism to avoid this, the manufacturing of the gas turbine blades should be controlled and monitored to minimise surface defects and residual stresses.

Sujata et al. [17] probed the failure of the gas turbine blade through micro structural study. Study revealed that most frequent failures were creep and stress rupture, which highly dependent on microstructures of the blade. Creep and stress rupture were facilitated because of the micro structural degradation which occur during the service exploitation. The paper reported some basic micro structural features of the cast nickel based super alloy which can control the failure mechanisms. Mazur et al. [18] were investigating a gas turbine blade failure. The blade was made from Inconel 738LC, a nickel based alloy. Because of working at high temperatures, the blades experienced internal cooling cracks at different air foil sections, and base alloy degradation. Aluminium coating was observed to be lost due to oxidation, reduced ductility and toughness because of carbon precipitation at the grain boundaries, proof of spread of intergranular creep cracks. The start and spread of the coating crack was also observed driven by the mixed fatigue/creep process [19,20]. Because of thermal fatigue the coating degradation facilitated the initiation of crack. Intergranular crack triggered and propagated due to creeping process [21,22].

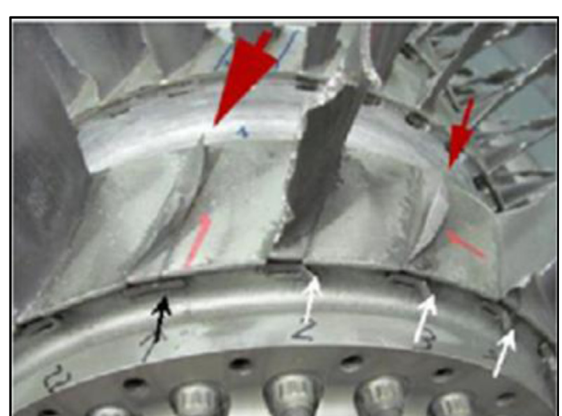
2.2. Failure mechanism of steam turbine blade

Plesiutschnig et al. [23] analysed the crack at the root of third blade of a LP (low pressure) steam turbine. The basic cause of fatigue was observed as pitting corrosion. The material used was forged ferritic/martensticX20Cr13. For the study of crack propagation stresses metallographic investigations, fracture mechanics analysis and FEA were used. After doing the experimentation and various calculations it was observed that erosion holes at root of blades increase the stresses concentration above the yielding stress. Changing the natural frequency by altering blade speed does not affect the crack spread. It was observed that unsteady steam pressure caused the bending and centrifugal loads that further propagate crack. From FEA local mean stress higher than 500 MPa at the blade's edge in un-notched conditions caused by rotor speed whereas in notched condition from FEA it was observed that the pitting hole increases the local stress beyond yield. Linear elastic fracture mechanics (LEFM) showed that the crack propagation was caused due to change in stress between 160 and 210 MPa. The beach marks i.e. damaging loading condition from 2 to 22 mm crack length was a minimum of 1500 and a maximum of 5000. And by varying the fluid flux by 450 times per year the crack took 3–11 years to grow from 2 to 22 mm. Operators in thermal power plant are advised to avoid deposits on the blades and to control the fluid flux variation numbers so as to prevent the failure.

Galina Ilieva [24], studied the erosion failure mechanism of steam turbine stage with twisted blade. The research was carried out on the steam turbine blade k-1000–6/1500 installed at a nuclear power plant. The main focus was on the amount of moisture in the stage to affect droplet diameter, mass flow rate and force on the surface of the blade. The investigation helped to define the trajectories of water particles, the causes of erosion were identified in certain sections of streamlined surfaces. It blade erosion rate was found a function of wetness percentage, particle velocity, flow angle, and shape shift of blade from hub to shroud. The larger drops of the condensate shown the most erosive effects. Shukla and Harsha [25] did the vibration response analysis of the last stage low pressure steam turbine blades. Authors aimed to find variation in the vibration response of the blades with the crack size. The crack at the root resulted in the loss of the stiffness in the region of the blade root, due to this the natural frequencies were shifted and dynamic and static stresses were also redistributed in blade root that might cause the failure of blade. Change in the natural frequency was the presented as an indication of the crack. It was advised to do natural frequency test of the blade during overhaul. Further, FEM analysis was used to validate the results. Azimian and Bart [26] did the computational analysis of blades of the inward flow steam turbine. The erosion observed was because of the steam flow comprising the solid particles. The results indicated that there were 3 main areas where pitting occurred. The first and the highly affected part was the trailing edge of stator blade. Second part was the leading edge of suction side. And the third region which eroded the least was the centre of the rotor blade. In the steam turbines, erosion and fatigue failures are mainly observed, but there were some other modes of failure like crack and pitting [27,28]. Some deposits were also observed on the blades which later on caused problems under operating conditions. Regular overhauling including frequency check can help in avoiding the failure [25,29].



(a)



(b)

Fig. 3. Installation of the compressor rotor displaying broken blades: (a) overall view of the damaged rotor installation and (b) overall view of the failed 1st stage compressor blades [16].

2.3. Failure mechanism of hydro turbine blade

Ramirez et al. [30] inspected the failure analysis of the runner blades of a Francis hydraulic turbine (Fig. 4). The study focused on evaluating the distribution of pressure on the edge, using CFD. Stress measurement was conducted using FEA, and a basic fatigue analysis was performed.

Natural mode of vibration in water, the frequencies of Von Karman served as the reference, and results showed great concentration of stress in the T-joint between blade and crown. Study showed that the stresses induced were below the yield strength, therefore, failure was not caused only by the stresses. The rise in the water level, at the outlet of the turbine, caused the stress to increase which might have accelerated the blade failure. From the pressure distribution cavitation prone areas were observed, the cavitation damage recorded at the time of the inspection. The natural frequency of the blades was increased at low loads which resulted in increased cycle stress of the runner blades. Therefore, the potential reason for failure was found as low loads during turbine operation. Dorji and Ghomashchi [31] presented the overview of the failure mechanisms of the hydro turbines. Authors studied four failure modes for Pelton, Francis, and Kaplan turbines. These modes were cavitation, erosion, material defect and penetration. Then, they reviewed that the failure due to pitting action of silt erosion where blade was subjected to cyclic stress, hence the blade failed might be due to the fatigue. Authors also observed that the blade would have failed due to material defects. Preventions could have been taken to avoid hydro turbine blade failure; such as installing the de-silting chamber to control the silt flow, use proper coatings like study revealed that TC based composites, and had better confrontation characteristics against sediment erosion, [32]. Guangjie et al. [33] conducted a study of the Francis turbine abrasion predictions based on the simulation of liquid–solid two phase gas. It was obtained that the blades were worn out because of the sediments in the flow. Relation was investigated between the wear rate and the sediment concentration. CFD was adopted for the simulation of the steady liquid–solid, two phases flow under various operating conditions. Finnie model was used for the prediction of the abrasion. Study revealed that wear rate of the blades increased with the increase in the concentration of the sediments [34]. The wear rate of the guide vanes was almost proportional to third of the power flow. The maximum wear rate occurred at the part load conditions and increased with the increase in the head.

2.4. Failure mechanism of wind turbine blade

Haselbach et al. [35] studied the failure of the trailing edge in the blade of the wind turbine at full scale. The techniques used were analyses of non-linear finite elements, and analysis of plane stress. The study shows that the progressive damage analysis (PDA) can boost wind turbine structure prediction capabilities. Study shows a novel approach in which author combines the simple solid elements coupled with the shell elements by using MPC leads to predict local trailing edge failure. Study reveals the importance of combined rotor blade testing. The deformation of the trailing edge contributed to failure due to combined charging. In combined loading trailing edge compressive loads were also subjected. Lee et al. [36] investigated the fatigue failure at the root end of a composite wind turbine blade. The finite element analysis was carried out by using subcomponent finite element (FE) solid model and a full scale FE shell model. The study showed that real load distribution at the root for a slender and a large wind turbine was different from that which was calculated by conventional approach. The blade shell's bumping motion altered the load distribution at blade root ends. The severe increase in loads led to the partial separation of T-bolt joint and delamination of the root end which may results in the pulling out of the blade from the wind turbine while operating. Chen et al. [37] provided insights into the failure of wind turbine big size blades. Author used 52.3 m composite blade for the study which was a example for 2.5 MW wind turbine. Blade was made of epoxy resin fused glass

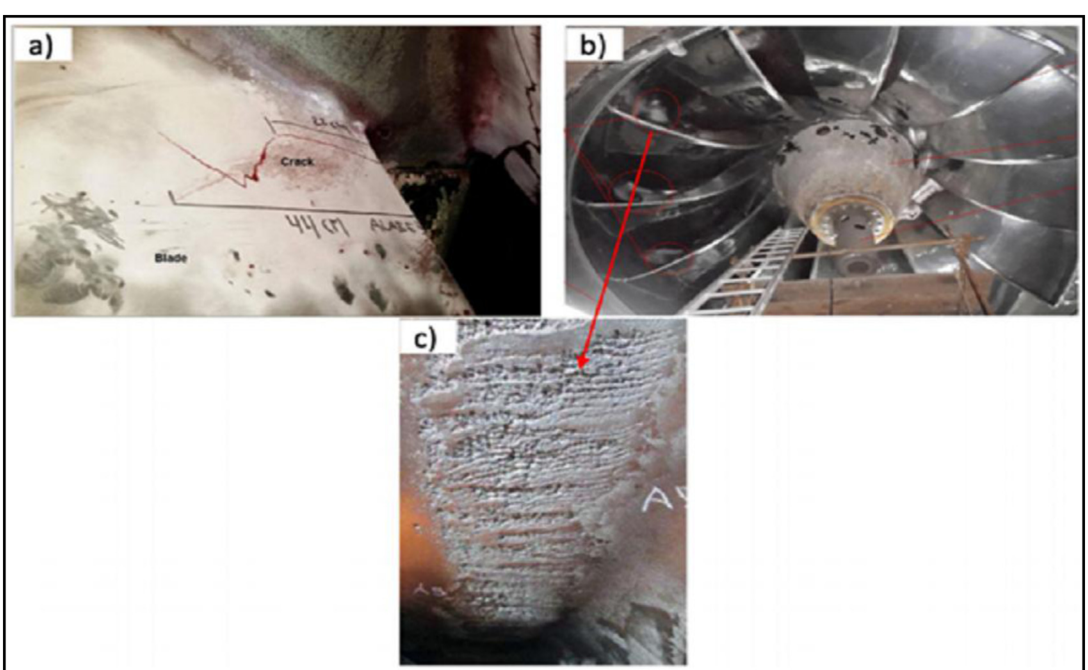


Fig. 4. (a) Crack on the trailing edge profile at the junction of the runner blade with the crown, (b) cavitation pitting damage near the trailing edge of the blade, (c) magnification of cavitation damage on the underside of the blade [30].

fabric and vacuum, and had traditional box-spar with 2 shear webs. At the outer and inner surfaces, spar caps have tri-axial laminates and also a sufficient quantity of unidirectional laminates between surfaces. The blade was charged with a state of static bending. It was found that in the fleeting area the blade exhibits several failure modes of laminate fracture, skin-core sandwich de-bonding, delaminating, and sandwich core failure and shear web fracture. Delamination of unidirectional laminates in spar cap has been identified as the plausible basic cause of disastrous blade failure. Producing energy by the use of wind turbines is eco-friendly. There are several modes of failure observed in the wind turbine blades like fatigue failure, creep, bending [36] etc. improvement in the design of blades and use of high strength materials helps in avoiding the failure.

2.5. Failure mechanism of other turbine blade

Zhang et al. [38] explored the fatigue failure mechanism of impellers and blades. Study showed that due to vibration high cycle fatigue was the main mechanism of failure. Fatigue failure was because of the material defects, structures, corrosion, erosion, etc. fatigue failure could be avoided from the aspects of the design, material selection, manufacturing, overhaul and operating conditions. Resonance because of the aerodynamic load was the reason for fatigue failure in the steady operating conditions. FEM, XFEM and BEM techniques were used for the numerical simulation. Wang et al. [39] explored the thermo mechanical fatigue (TMF) failure of a single crystal nickel alloy. The test rig was consisting-loading, synchronizing, cooling, heating and some monitoring systems. No crack was initiated at the blade tip. It was observed that TMF failure occurred at suction side close to the trailing edge. Further study revealed that TMF crack was initiated at the pin–fin fillet. After this the crack was propagated towards the outside wall. Study showed that use proper TMF resistance at pin–fin fillet and lower the operating temperature. Xue et al. [40] analysed the fretting fatigue failure of the nuclear power plant turbine blade. The basic cause was low clearance between blade and disk which caused sliding motion and led to fretting failure during the operation. The fretting wear was propagated by high cycle fatigue. Micro oxide particles were present at fatigue initiation region which were the typical evidence of the fretting wear. Non-linear elastic–plastic FEM, EDS were used. Results showed that the location of the maximum stress was different from the fatigue crack initiation region. The fretting fatigue failure was caused because of the combined action of the fretting wear and relatively high stress. The failure mechanisms can be avoided by the use of proper periodic NDI inspection.

Das et al. [41] examined the failure of a 220 MW thermal power plant low pressure (LP) turbine blade. The blade used was made of stainless steel martensitic, and martensitic tempered structure. Study showed there was no sign of blade content degradation. The fracture occurred 113 m from root of the blade at aerofoil region. There were several pits at the edge, and chloride was found in these pits which caused corrosion of the type of crevice. Visual inspection, chemical analysis, SEM and fractography supported the results. The blade surface deposits contain silicon (Si) and expected it to come about because of the impingement of silica particles that led to the formation of the pits. To prevent the chemistry of the crevice corrosion water should be balanced and the silica and chloride levels should be managed. Salam et al. [42] investigated the creep-fatigue failure in the aero engine turbine blade. It was found that one second stage turbine blade was broken during the initial investigation time. Metallurgical study revealed that at elevated temperatures fractured blade was under an abnormally high stress. The given situation caused triple point crack (w-crack) on the blade to creep and build. Those cracks were the sites of initiation for fatigue failure. The blade failed due to tiredness under conditions of low period fatigue. Magnetic testing of fluorescent particles (MPFI) was conducted for metallurgical investigations. Magnetic testing of fluorescent particles (MPFI) was conducted for metallurgical investigations. Other techniques used were EDS, SEM and visual inspection. R. Viswanathan [43] examined the failure of the blade in the combustion turbines. Results showed that the failure was caused by creep aided by the climate, which was similar to corrosion by stress. Grain boundary spikes window was observed at the region of the failure. The overlapping of the corrosion window and the stress window was the cause of corrosion on the creep and grain boundaries. From the analysis it was clear that when the machines were run at different ratings, the type of corrosion of blades remained unchanged but the degree and position of the corrosion characteristics were systematically changed. Adequate amount of evidence was gathered to show that the malfunction was not caused by zinc. Use of the coating can provide an effective solution to the problem. Visual examination, metallurgical inspection, micro specimen analysis, Auger electron microscopy and X-ray diffraction were the techniques used.

Some preventive steps are discussed in next section give an idea about the delaying or avoiding the failure. Preventive techniques like use of resistive materials for the coating of blades, designing the aerofoils, controlling the peak temperatures of the working fluid in the steam and gas turbines, avoiding the foreign body injection in the hydro turbines and regularly overhauling should be used.

Table 1 gives a brief idea about the failure of blades and the various techniques used so far which are discussed above in detail. Some preventive steps are also discussed in the table which gives an idea about the delaying or avoiding the failure. Preventive techniques like use of resistive materials for the coating of blades, designing the aerofoils, controlling the peak temperatures of the working fluid in the steam and gas turbines, avoiding the foreign body injection in the hydro turbines and regularly overhauling should be used.

3. Preventive measures

Preventive measures are the steps which are taken to control or delay the failures in the turbine blades. Some of the preventive measures which are taken to enhance the service-life of the blade are discussed in brief –

3.1. Preventive measures in gas turbines

During the scheduled maintenance including the cleaning of the cooling holes, turbine blades should be recoated with the thermal barrier coating [13,44,45]. Use hot corrosion resistive material like chromium. Study showed that minimum 16% of Cr by weight is required in the alloy IN738LC for good hot corrosion resistance [46,47]. Failures can be avoided by manufacturing the blade surface defect and residual stress free [48]. Focus should be on that during manufacturing there should be no localized carbon [49]. In the gas turbine the number of start-up and shutdown should be as less as possible [50]. For getting the increase in the service life of the blade there should be improvement in the cooling system of the blade, further thermal gradients and thermal stresses of the air foil should be minimized [18].

3.2. Preventive measures in steam turbines

As evident in the literature that the pitting corrosion is one of the major reasons for the initiation of the crack in the steam turbines which is mainly caused due to the moist oxygen-laden atmo-

Table 1
Recent trends in tools/techniques used in failure analysis/investigation of turbine blade such as EDS (Energy Dispersive Spectroscopy), SEM (Scanning Electron Microscope), XRD (X-Ray Diffraction), AFM (Atomic Force Microscopy), FEM (Finite Element Method), FPI (Fluorescent Penetrant Inspection), CFD (Computational Fluid Dynamics) and EBSD (Electron Backscatter Diffraction).

Year	Author	Type of Turbine	Material of Blade	Tools or Techniques (analysis/ investigation) used	Remarks
2016	Rani et al. [13]	Gas Turbine	Superalloy IN738LC	• EDS • SEM	• In this paper the tip cracking of the first stage gas turbine blade of the thermal power plant was investigated. • Corrosion pits were observed. • Blade failed due to the surface degradation because of overheating, oxidation and hot corrosion. • Crack was investigated at the trailing edge. • Study showed that better corrosive resistant materials prevent such failures.
	Khan et al. [14]		Superalloy Udimet 500	• Visual Inspection	• The intergranular corrosion in second stage gas turbine blade was examined. • Chromium carbide was precipitated at the grain boundaries on exposure to 900C and huge chromium carbide precipitates at the grain boundaries on the exposure to 950C because of intergranular corrosion. • Pitting was found on the grains and also at the grain boundaries. • Due to pits stress was concentrated and the intergranular crack initiates. • To control this temperature control was required by using thermal barrier coatings.
2015	Camacho et al. [15]		High Strength Stainless Steel Having Elements Like Cr, Ni, Fe And C	• XRD • SEM • AFM	• The wear damage of gas turbine blade was studied. • The modes of the wear were severe pitting action, corrosion few irregular scratches, large craters similar to erosion. • The higher values of the degradation of the surface were reached in low pressure side of the blade.
2014	Maktouf et al. [16]	Gas Turbine	UNS N07718 Complying With ASTM B637	• FEM • SEM • EDS • FPI • Stereo-Microscopy	• The failure of first stage compressor blade of the gas turbine was investigated in this paper. • Blade failed due to high cycle fatigue mechanism. • Such failures can be avoided by manufacturing the blade surface defect and residual stress free.
2010	Sujata et al. [17]		Nickel Based Super Alloy	• Microstructural study	• In this paper the failure of the gas turbine blade through microstructural study was studied. • Most frequent failures were creep and stress rupture, which strongly dependent on microstructures of the blade. • The paper reported some basic microstructural features of the cast nickel based superalloy which can control the failure mechanisms.
2005	Mazur et al. [18]		Nickel Based Alloy Inconel 738LC	• FEM • Metallographic Investigation	• The failure of a gas turbine blade was investigated. • The blades experienced internal cooling cracks at different airfoil sections and the degradation of the base alloy because of working at high temperatures. • Aluminium coating was lost due to oxidation, decreased alloy ductility and toughness because of carbon precipitation at the grain boundaries, evidence of intergranular creep crack propagation. • The thermal fatigue facilitated the crack initiation. • The blade cooling system should be improved by reducing the thermal gradients of the airfoil to prevent the failure.
2003	Khajavi et al. [19]		Alloyed Steel	• SEM • XRD	• The failure of first stage gas turbine blades was studied. • Study was carried out on the blades of a GE-F5 gas turbine. • Blade suffered the hot corrosion and the hot corrosion erosion. • The high temperature hot corrosion was the dominating one. • Corrosion oxides of chromium and nickel were present in greenish colour.
	Chang et al. [20]	Gas Turbine	Superalloy GTD-111	• Visual Inspection • FEM	• In this paper the failure of gas turbine first stage bucket was investigated. • Crack was induced because of thermal mechanical failure. • Peak stress and maximum temperature were observed in the failed region.
2001	Gallardo et al. [21]		Nickel Super Alloy CMSX-4	• SEM • XRD • SEM-BSE	• The failure of the first stage blade of a gas turbine was studied in this paper. • Blade tips suffered hot corrosion. This took place nearly 760C. • Spotty attacks of hot corrosion were also there in un-worn region. • The deterioration was much localized.
2000	Hou et al. [22]		Composite	• Non-Linear Finite Element Method	• The fatigue failure of gas turbine blades by mechanical analysis was studied. • Blade failure was considered to be the mixture of high cycle fatigue and low cycle fatigue. • The maximum stress occurred at the top firtree. • No gas dynamic fluctuations observed.

Table 1 (*continued*)

Year	Author	Type of Turbine	Material of Blade	Tools or Techniques (analysis/ investigation) used	Remarks
2016	Plesiutschnig et al.[23]	Steam TurbineSteam Turbine	Ferritic/Martensticx20cr13	• Metallographic Investigation • FEA • Linear Elastic Fracture Mechanics (LEFM)	• In this paper the crack at the root of third blade row of LP (low pressure) steam turbine was analysed. • Corrosion pits at the root increased the stress above yield stress. • The basic cause of fatigue crack initiation observed was pitting corrosion. • Avoid the deposits on the blades and fluid flux variation numbers to prevent the failure.
	Galina Ilieva Ilieva [24]		Composite	• Visual Inspection • GAMBIT Software	• The erosion failure mechanism steam turbine stage with twisted rotor blade was studied. • The research was done on k-1000–6/1500 steam turbine blade working in nuclear power plant. • Study helped in specifying the trajectories of water particles, the reasons of erosion and the erosion at certain parts of streamlined surfaces were established. • Erosion rate of blade was a function of wetness percentage, velocity of particle, flow angle and change in the shape of the blade from hub to shroud.
	Shukla and Harsha [25]		X10crnimov1222	• FEM	• The vibration response analysis of the last stage low pressure steam turbine blades was done. • The crack at the root resulted in the loss of the stiffness in the region of the blade root. • Change in the natural frequency was the indication of the crack. • It was advised to do natural frequency test of the blade during overhaul.
	Azimian and Bart [26]		Stainless Steel 510	• CFD	• The computational analysis of blades of the inward flow steam turbine was studied. • 3 main areas where erosion occurred. • The first and the most affected part was the trailing edge of stator blade. • Second part was the leading edge of suction side. • The third region which eroded the least was the centre of the rotor blade.
2015	He et al. [27]		Fv448	• SEM • XRD • EBSD	• The fatigue crack growth behaviour in low cycle fatigue conditions in a shot peened LP steam turbine blade was examined. • Fatigue crack aspect ratio was investigated. • The aspect ratio in case of polished sample was nearly 1.0–1.2 and when the crack length increased aspect ratio decreased to 0.8. • In T0 case the aspect ratio was low at the initial stage but when the crack propagates it was increased. • T0 exhibited the best fatigue life. • The crack growth behavior was similar in the polished and the ground case, while the crack growth in shot peened case was significantly delayed.
2014	Shlyannikov et al. [28]		12Cr Steel	• Stress-Strain Analysis • Experimental Study	• The fatigue of the steam turbine blades was studied. • Author studied about fatigue life of the cracked steam turbine blade. • Static and cyclic tests were done for obtaining the mechanical properties and fatigue life characteristics.
2013	Ziegler et al. [29]		X20Cr13 Steel	• SEM • Optical Microscope • Brinel Hardness Test	• This paper gives an idea of the failure of low pressure steam turbine blade of a power plant. • Failure was at the aerofoil at a distance of 150 mm from the root. • Pits were observed having chloride at the edges. • Intergranular micro crack was initiated due to the residual stresses.
2015	Ramirez et al. [30]	Francis Hydraulic Turbine	13cr/4ni	• CFD • FEA	• This paper examined the failure analysis of the runner blades of a Francis hydraulic turbine. • Results showed large concentration of stress in T-joint between blade and crown. • The crack was originated at the joint. • The rise in the water level at the outlet of the turbine caused the stress to increase which might have accelerated the blade failure. • At low loads the natural frequency of the blades was increased resulting in high cycle fatigue of the runner blades.
2014	Dorji and Ghomashchi [31]	Hydro Turbine	Ductile Matrix/Ductile Fibre Composite	• CFD	• The paper gives the overview of the failure mechanisms of the hydro turbines. • Blade failed due to pitting action of silt, cause erosion. • Blade was subjected to cyclic stress, hence the blade failed due to fatigue. • The de-silting chamber to control the silt flow. • Tungsten carbide based composites for e.g. 86WC-10Co-4Cr [32], have improved resistance characteristics against sediment erosion.

(*continued on next page*)

Table 1 (*continued*)

Year	Author	Type of Turbine	Material of Blade	Tools or Techniques (analysis/ investigation) used	Remarks
2013	Guangjie et al. [33]	Francis Turbines	TungstenCarbide Coating Composite	• CFD	• The abrasion predictions for the Francis turbines were done. • The blades were worn out because of the sediments in the flow. • Relation was investigated between the wear rate and the sediment concentration. • Wear rate of the blades increased with the increase in the concentration of the sediments. • The maximum wear rate occurred at the part load conditions and increased with the increase in the head.
2016	Haselbach et al. [35]	Wind Turbine	Unidirectional Fibre Composite	• Non-Linear Finite Element Analysis • Plane Stress Analysis	• The trailing edge failure in the full scale wind turbine blade was studied in this paper. • The progressive damage analysis (PDA) can enhance the prediction capabilities of wind turbine structure. • A novel approach for prediction of failure of local trailing edge was developed. • The trailing edge deformation led to failure was due to combined loading.
2015	Lee et al. [36]		Glass NCF/Epoxy Composites	• FEA	• The investigation was on the fatigue failure of composite wind turbine blade at the root end. • Study showed that real load distribution at the root for a slender and a large wind turbine was different from that which was calculated by conventional approach. • The severe increase in loads led to the partial separation of T-bolt joint and delamination of the root end.
2014	Chen et al. [37]		Glass Fabric And Vacuum Fused With Epoxy Resin	• Visual Inspection	• This paper provides the insights into the failure of the large size blades of wind turbines. • The blade was loaded with static bending condition. • The blade exhibits multiple failure modes of laminate fracture, sandwich skin-core de-bonding, delamination, sand wich core failure and shear web fracture. • Delamination was the basic cause of the catastrophic failure.
2014	Xue et al. [40]	Low pressure turbine	0Cr17Ni4CuNb	• Non-Linear Elastic-Plastic FEM • EDS	• The analysis was done of the fretting fatigue failure of the nuclear power plant turbine blade. • Small space between blade and disk caused sliding motion and led to fretting failure during the operation. • The fretting wear was propagated by high cycle fatigue. • The failure mechanisms can be avoided by the use of proper periodic NDI inspection.
2003	Das et al. [41]		Martensitic Stainless Steel	• SEM • Fractography • Chemical Analysis	• The failure of low pressure (LP) turbine blade of 220 MW thermal power plant is reviewed in this paper. • The fracture occurred at aerofoil region 113 m from root of the blade. • The mode of the failure was intergranular type. • Several pits having chloride were found at the edge • To avoid the crevice corrosion water chemistry should be balanced and the level of silica and chloride should be in control.
2002	Salam et al. [42]	Aero Engine Turbine	Composite	• Magnetic Particle Fluorescent Inspection • EDS • SEM	• The creep-fatigue failure in the aero engine turbine blade was studied. • Metallurgical study revealed that fractured blade was under abnormally high stress at the elevated temperatures. • Triple point crack (w-crack) on the blade was the initiation for the fatigue failure.
2001	Viswanathan [43]	Combustion Turbines	Udimet 710	• Auger Electron Microscopy • Microprobe Analysis • XRD	• The failure of the blade in the combustion turbines was examined. • The failure was caused by the environment assisted creep which was similar to stress corrosion. • The superimposition of the corrosion window and the stress window was the reason for creep and grain boundary corrosion. • The failure was not caused because of the presence of zinc. • Use of the coating can provide an effective solution to the problem.

sphere [51]. The designer and the operator of steam turbines should consider the various factors like excitation of the natural frequency, the viable crack size, etc. [52]. Due to the excessive deposition of the Na_2So_4 and $CaSo_4$, the material of the blade was not able to form a protective layer of oxide which promotes the crack initiation [53]. It is recommended that avoid the deposition of the foreign particles is the only preventive solution which can minimize the fluid flux variation number as well [54,55].

3.3. Preventive measures in hydro turbines

Hydro turbines may fail because of cavitation, erosion, material defects, etc. [56,57]. The cavitation occurs because of the formation of the vapour bubbles [58]. The bursting of these bubbles may lead to failure. Change in the design of the blade profile, use of cavitation resistive materials like work hardenable materials, composites (fibres normal to the surface), draft tubes in reaction turbines, etc.

can help in avoiding the cavitation [59,60].While the erosion in hydro turbines takes place because of the flow of high velocity fluid and the impingement of the sediments on the turbine surface [61]. Study showed that TC based composites have improved resistance characteristics against sediment erosion [62]. To minimise erosion SS with 13% Cr and 4% Ni should be used.

4. Conclusion

It is concluded from the literature that there are certain specific failures that occur in some specific turbines i.e. corrosion is mainly observed in thermal power plant turbines, erosion is observed in hydro turbines etc. The studies revealed that the blades used in the steam turbine fail generally due to high temperature, fatigue, and corrosion. The blades of the wind turbines fail due to fatigue and creep. There are several other failure modes like crack initiation and propagation, tearing, scratches etc. Many authors recommended the use of SEM, FEM, XRD techniques for the investigations of failure. Some preventive techniques like coating of the blades with some resistive material delayed the failure. However improved manufacturing and design can also help in increasing the service life of the turbine blades. In case of steam and gas turbines the control of maximum temperature is one of the important factors to avoid the failure. The literature shows that a lot research analysis is carried out on the failure of turbines in recent years, but few studies are reported on the preventive methods to avoid failure and recommended as a future scope for the researchers of the field.

CRediT authorship contribution statement

Satyender Singh: Conceptualization. **Manjeet Kharub:** Writing - original draft. **Jagdeep Singh:** Writing - original draft. **Jaspreet Singh:** Writing - review & editing, Supervision. **Vivek Jangid:** Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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