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Comprehensive Insight into the Failure Mechanisms, Modes, and Material Selection of Steam Turbine Blades

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Abstract

Addressing the critical issue of turbine blade failures, particularly in steam turbine systems, this comprehensive review delves into examining and analyzing various failure mechanisms associated with steam turbine blades. The discussion extends to the mode utilized in investigating these failures, with a specific focus on the crucial role of steam turbines in power generation. The review synthesizes various studies that have explored suitable blade materials for optimized performance and reduced failure risks. Findings reveal common failures such as thermal stress, mechanical stress, corrosion, erosion, fatigue, and creep in turbine blades and hubs. Consequently, the review serves as a valuable resource, providing insights into failure mechanisms and advocating for the implementation of suitable materials to enhance the reliability and performance of steam turbine blades.

Keywords: *blade material; creep; erosion; failure mechanisms; fatigue; material selection; steam turbine blade*

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1. Introduction

Steam turbine engines provide approximately 88% of the nation's electricity in power plants, according to the USAGov (2023). The worldwide steam turbine market is predicted to expand 2.5% from 2023 to 2030 in 2022. The need to solve energy imbalances is pushing the construction of new power plants, which will increase steam turbine demand. According to marketresearch.com (2023), combined-cycle natural gas plants, which are reliable energy sources, are driving steam turbine demand worldwide. Steam turbines employ pressurized steam's thermal energy to generate mechanical work through a revolving output shaft. Charles Parsons invented modern steam turbines in 1884 (Richardson, 2014). Since then, improved metalworking processes have been used to mold high-grade steel alloys into precision steam turbine components. Steam turbine durability and efficiency have improved due to 20th-century manufacturing advances. The energy economics of the 21st century depend on steam turbine technological advancement (Leyzerovich, 2021). Steam turbine blade failure refers to the condition where one or more blades in a steam turbine experience mechanical damage or failure. These failures can occur due to various factors, including mechanical stress, material fatigue, corrosion, erosion, or manufacturing defects (Singh et al., 2021). The complexity of blade behavior is influenced by several factors, including temperature, vibration, stresses, material blade design, and maintenance effects. Researchers have found that these factors play a significant role in influencing the blade's behavior. This scientific paper consolidates much of the past and present research on steam turbines, discussing their revolutionary discoveries and limitations. This review article discusses steam turbine causes and effects after reviewing many case studies. It also discusses studies on blade materials for optimal performance and low failure risk. Thus, it is crucial to build the best steam turbines by avoiding the causes and following the recommendations of this paper.

2. Failure mode to failure mechanism of steam turbine blade.

A turbine's blades are designed to control the speed, direction, and pressure of the steam as it passes through the turbine (Singh et al., 2021). For large-scale turbines, there are dozens of blades attached to the rotor, typically in different sets. Each set of blades helps to extract energy from the steam while also keeping the pressure at optimal levels (Tanuma, 2022). The failure mode of these blades in steam turbines is attributed to mechanisms such as fatigue and the presence of significant thermal or mechanical loads, leading to the formation of fractures, pits, and material degradation (Chowdhury et al., 2023). The transition from failure modes to specific failure mechanisms and their contributing factors in turbine blade failure will be briefly discussed below.

a) Thermal stress

Thermal failure in steam turbines refers to the failure of turbine components due to excessive heat generated during operation. This can lead to deformation, cracking, or other forms of damage to the turbine blades and other components (Kumar, & Reddy, 2022). Numerous studies have investigated high-temperature low-cycle fatigue (LCF) and creep-fatigue interactions in steam turbine steels. The notable creep resistance of 9-12% Cr martensitic steels make them suitable for high-temperature steam turbine components. Fatigue life predictions under thermo-mechanical fatigue (TMF) conditions have also been explored for 9-12% Cr steels (Azeez, 2021). It was found by Mukherjee et al., (2022) that the thermal failure of Inconel 718 and 17-4Ph Stainless Steel steam turbine blades are caused by rotational load, bending forces from steam mass flow, and hot corrosion. These factors induce stress and strain on the blades, which can ultimately lead to failure. In Banaszkiewicz (2018) study, numerical investigations were conducted to identify life-limiting locations and evaluate fatigue life for crack initiation in the intermediate pressure steam turbine rotor. The results showed that heat grooves are critical areas in terms of thermal fatigue, and thermomechanical fatigue was identified as a cause for crack initiation in impulse steam turbine rotors.

b) Mechanical stress and vibration effect

The mechanical stress experienced by turbine blades is intensified by unsteady dynamic stresses and high centrifugal forces, ultimately leading to failure. Turbine failures often occur due to blade fatigue induced by vibrations and resonance. Rani et al., (2019) conducted a modal analysis in order to accurately determine the specific locations of fractures and identify failure modes resulting from structural vibrations, hence assuring the secure functioning of turbines. According to Kumaraswamy, & Raju (2019), the blade experiences mechanical stresses owing to factors such as steam pressure, steam temperature, and centrifugal forces resulting from its circular movement. Shukla, & Harsha (2016) conducted a vibration response analysis using the Finite Element Method (FEM) on the last stage low-pressure steam turbine blade X10crnimov1222. The study revealed that blade cracks are caused by vibration effects, resulting in a loss of stiffness near the blade root. In Benammar, & Tee (2023) research, mechanical unbalances such as friction, wear, corrosion, erosion, blade rupture, thermal unbalance, and evaluative unbalance were investigated in steam turbine components, including blades, bearings, couplings, gearboxes, generators, and valves. Benammar, & Tee (2023) proposed a novel approach using the Fault Tree (FT) method and Artificial Neural Network (ANN) method for real-time failure diagnosis in the Cap-Djinet thermal power plant's steam turbine. The hybrid method combines these two techniques to accurately and efficiently detect failures. The study concluded that the proposed approach is effective in automating diagnostic tasks, emphasizing the swift identification of potential failure causes through reliable deep neural network learning, utilization of sensor data for fault diagnosis to avoid excessive sensor usage, and the importance of accurate data from both sensor-based and descriptive methods.

c) Corrosion

Corrosion is a significant concern in steam turbines due to their exposure to fuels containing corrosive elements such as sulfur, vanadium, lead, sodium, and pollutants from air or saltwater (Rodrígez Ramírez et al., 2023). These elements can generate alkali metals, causingsevere corrosion of turbine blades and leading to their failure (Yadav et al., 2018). In a study by Katinić, & Kozak (2018), a historical case of rotor blade fracture due to corrosion fatigue in an industrial steam turbine at the Petrokemija Kutina fertilizer production plant in Croatia was investigated. The failed blades were from the turbine stage in the salt zone, and vibration analysis pinpointed the loss of rotor blades and the shroud band as the main causes of vibration. A significant resonant vibration peak exceeding 200 µm pp was detected during turbine shutdown. Visual inspection confirmed the absence of two blades and their section of the shroud band from the 5th rotor wheel (as depicted in Figure 1). To resolve the issue, the damaged rotor was replaced, and repairs were completed, resulting in low and acceptable vibration levels of 15 µm pp when the unit was put back into operation.

In a study by Plesiutschnig et al., (2016), a crack at the root of the third blade row in a low-pressure steam turbine was investigated. The turbine blade material was Ferritic/Martensitic x20cr13. Corrosion pits at the root were observed to increase stress beyond the yield point, and pitting corrosion was identified as the primary factor leading to fatigue cracks. The propagation of these cracks was influenced by centrifugal stress and superimposed bending loads induced by unstable steam forces. In another study, Puspasari et al., (2021) examined the impact of tempering treatment on the resistance of modified cast CA6NM stainless steel to pitting corrosion in a 3.5% NaCl solution. The findings indicated that tempering treatment had the potential to enhance the resistance of modified cast CA6NM stainless steel to pitting corrosion. Pitting corrosion, often induced by specific environments such as chloride or sulfide solutions, was highlighted as a potential cause. Additionally, Xie et al., (2020) analyzed the causes of cracking in the last-stage blade of a low-pressure rotor in a thermal power plant, attributing it to the accumulation of corrosive chloride ion (Cl^-) on the blade surface, leading to stress corrosion microcracks. These microcracks extended under cyclic excitation stress during rotor rotation, resulting in fatigue cracking. The paper recommended replacing cracked blades and inspecting others for similar issues to ensure unit safety and stability.

Kshirsagar, & Prakash (2019) introduced an innovative approach to forecast the corrosive effects on turbine blades, employing modal and harmonic studies. This study examined various corrosion parameters, including depth, degree of surface corrosion, and corrosion spatial distribution. It established a quantitative model linking the percentage change in natural frequency and amplitude of corroded blades with blade loss, dynamic strain concentration, and crack size distribution. Simulation results were analytically validated and compared to finite element analysis, demonstrating significant agreement. This methodology offers a solution to prevent unforeseen steam turbine outages due to corrosion-induced defects. Adnyana (2018) investigation concerned low-pressure steam turbine blades experiencing corrosion fatigue due to cavitation erosion and fatigue. Metallurgical evaluation attributed blade failure to corrosion fatigue initiated from pit-like flaws, signifying cavitation erosion. Similar instances of cavitation erosion were found on the leading edge, and the fatigue crack propagated tangentially to the nearest compromised edge, leading to ultimate fracture.

Figure 1 The Fracture at the root of the 5th rotor wheel's blade. Adapted from "Steam turbine moving blade failure caused by corrosion fatigue - case history" by Katinić, & Kozak (2018).

d) Erosion

Erosion on turbine blades can occur due to deposits, corrosion, solid particle erosion, and mechanical damage (Yadav et al., 2018; Ilieva, 2016). These factors, including dirt and dust deposits, corrosion from moisture or corrosive substances, solid particle impact, and mechanical damage, gradually wear down the blade surface over time. The findings from the cited studies include the significant impact of erosion on turbine blade efficiency and safety (Yadav et al., 2018; Thijel et al., 2021), the use of innovative techniques such as drainage grooves and hot steam injection to mitigate erosion and improve turbine performance (Hosseini et al., 2023; Hosseinizadeh et al., 2023), the influence of NaCl concentration on erosion and efficiency (Zhang et al., 2023), and the effectiveness of Bayesian network models in diagnosing damage mechanisms during blade failures (Quintanar-Gago et al., 2021).

Yadav et al. (2018) highlighted that turbine surface roughness up to 0.05mm can decrease efficiency by 4% and increase steam consumption. Therefore, it is crucial to maintain the turbine blade surface to prevent erosion and ensure turbine efficiency. According to Thijel et al., (2021), erosion-corrosion, influenced by fluid velocity, temperature, pH, and impurities, is a type of corrosion resulting from the combined effect of mechanical wear and corrosion. These factors affect the rate of material loss and, consequently, impact blade life efficiency. Additionally, erosion of Thermal Barrier Coatings (TBCs) on turbine blades is a frequent occurrence that can lead to the loss of protection, increased oxidation, reduced efficiency, and potential structural damage. Bogdan et al., (2021) found that an increased operating time significantly deteriorates blade condition parameters, as evidenced by changes in blade surface color. Hence, it is vital to monitor and address erosion issues in order to preserve the longevity and performance of turbine blades.

Hosseini et al., (2023) investigated erosion and mechanical damage in the last stage of a steam turbine, focusing on minimizing losses and prolonging turbine lifespan. They used the TOPSIS algorithm and mathematical equations to assess erosion and proposed the implementation of drainage grooves to reduce condensation losses, erosion rate, and entropy generated in steam turbine blades, primarily addressing erosion rate as a criterion. Hosseinizadeh et al., (2023) examined the detrimental effects of water droplets on turbine blade efficiency and safety and introduced a method for mitigating these effects through hot steam injection, using genetic algorithms to optimize injection parameters. The study's results demonstrated that hot steam injection led to a decrease in condensation loss, erosion rate, and blade inlet flow rate by 21%, 89%, and 4.9%, respectively, while increasing produced entropy by 22% under ideal conditions.

Zhang et al., (2023) examined erosion caused by excessive NaCl concentration in steam turbine blades, exploring its impact on the non-equilibrium condensation process and associated losses. The study revealed a significant influence of NaCl concentration on condensation loss and entropy generation, with reductions of 9.2% and increases of 42% at varying NaCl concentrations. The highest isentropic efficiency of approximately 0.884 was achieved at a specific NaCl particle number. The research emphasized how NaCl presence affected the non-equilibrium condensation process, resulting in efficiency loss, blade erosion, and safety risks. In a separate study, Quintanar-Gago et al., (2021) investigated multiple damage mechanisms, such as droplet erosion, corrosion, cracking, and fatigue, in low-pressure steam turbine rotating blades. They introduced a Bayesian network model to analyze failure and damage mechanisms, demonstrating its effectiveness in identifying the most likely damage mechanisms during blade failures, aiding in accurate fault diagnosis. Thijel et al., (2021) examined the fracture of a low-pressure steam turbine blade in an Iraqi refinery, attributing it to erosion-corrosion pitting and a decrease in material strength. Mechanical tests revealed that increased material hardness and decreased ultimate tensile stress and yield stress compromised material strength, leading to fracture. Chemical tests and microstructure analysis, however, indicated no difference in the microstructure and chemical composition of the blade alloy. Yadav et al., (2018) studied the impact of foreign particles on various steam turbine components, including rotor, bearing, thrust pad, gear pump turbine gear, throttle valve, emergency stop valve, and blades, highlighting how erosion and particle deposits can cause defects and lead to reduced steam flow and increased axial thrust. Azimian, & Bart (2016) conducted computational analysis on an inward-flow steam turbine's blades, identifying the areas most affected by erosion: the trailing edge of the stator blade, the leading edge of the suction side, and the center of the rotor blade. Erosion was linked to ingested steam flow containing solid particles.The studies highlight the importance of erosion and damage mechanisms in steam turbine blades and their impact on efficiency, safety, and lifespan. Deposits, corrosion, solid particle erosion, and mechanical damage gradually degrade the blade surface, reducing performance and increasing the risk of failures. These findings stress the need for proactive measures, including maintenance, design optimization, and effective monitoring, to mitigate erosion and damage. By doing so, steam turbines can maintain their longevity, efficiency, and safety, ensuring reliable operation across diverse industrial applications.

e) Fatigue failure

Fatigue failure is a prevalent factor contributing to the failure of steam turbine blades, occurring when fractures surpass the fracture toughness of the material constituting the blade. According to Cano et al., (2019), fatigue failure can present itself in two forms: low cycle fatigue and high cycle fatigue. The fatigue endurance of blades is subject to several parameters, including the composition of the blade material and the magnitude of the cyclic loads they undergo (He et al., 2023). In their study, Zhao et al., (2018) investigated the failure of a low-pressure steam turbine blade. Their analysis uncovered several key findings, including the presence of intergranular cracking, fatigue striations, and fretting wear characteristics. Additionally, the researchers determined that the maximum Von Mises stress experienced by the blade was measured to be 579 MPa, a value that falls below the yield strength of the 0Cr17Ni4Cu4Nb stainless steel material from which the blade was constructed.

Krechkovska et al., (2023) analyzed fatigue fracture characteristics in steam turbine rotor blades made of high-alloyed heat-resistant steel 15Kh11MF as shown in Figure 2. Factors contributing to early failure included extensive corrosion-erosion wear, uneven microstructure, and the presence of micro defects in surface layers, influenced by corrosive steam-water interaction in the phase transition zone. The study also assessed the structural and mechanical condition of high-alloyed heat-resistant steels in turbine rotor blades after varying durations of operation. In a separate study, He et al., (2023) investigated early failure in a steam turbine blade within a power plant, specifically the fourth-stage moving blade of the low-pressure rotor. The blade was made of 12Cr12Mo martensitic heat-resistant stainless steel. Mechanical testing and microscopy, including SEM and EDS, revealed an excessive presence of banded δ ferrite as a factor contributing to reduced fatigue and endurance strength. This issue likely stemmed from inadequate heat treatment or insufficient control of forging temperatures.

Kumar et al., (2020) examined the fatigue behavior of superalloy turbine blades under high-temperature and pressure conditions, revealing significant temperature effects on thermal stresses, especially in aluminum alloy blades. Cano et al., (2019) investigated the factors contributing to steam turbine blade failure, emphasizing low cycle fatigue and strain cycling fatigue mechanisms. They found that centrifugal forces in the last stage of a turbine can initiate and propagate cracks, while steam forces have a lesser impact. They recommended considering these findings in blade design for high-stress scenarios. Tian et al., (2019) focused on mechanical and corrosion fatigue fractures in steam turbine blades, stressing the importance of regular blade inspection during refueling outages and suggesting suitable non-destructive testing methods. Corrosion fatigue fracture was identified as a common cause of blade cracking. Bhagi et al., (2018) conducted a dynamic stress analysis of L-1 low-pressure steam turbine blades, indicating that while centrifugal forces and stresses remained within safe thresholds, high dynamic stresses combined with centrifugal load stresses could lead to fatigue failures in these blades.

The research findings illuminate the causes and characteristics of fatigue failure in steam turbine blades, a common issue marked by crack propagation beyond the blade material's fracture toughness. Blade material, cyclic stresses, and operational conditions significantly influence fatigue life. Technological defects, corrosion-erosion wear, and uneven microstructure can contribute to early failure in high-alloyed heat-resistant steel blades, often tied to inadequate heat treatment or forging temperature control resulting in excessive δ ferrite presence and reduced fatigue strength. Temperature and pressure have a substantial impact on thermal stresses in turbine blades, underscoring the importance of thermal considerations in blade design. Centrifugal forces play a more significant role in crack formation than steam forces. Routine non-destructive testing is critical for defect detection and accident prevention. High dynamic stresses, combined with centrifugal loads, may lead to fatigue failures in low-pressure steam turbine blades, emphasizing the need for stress-aware blade design.

f) Creep Failure

Creep, a phenomenon where blade materials deform permanently under high stresses below their yield strength, is exacerbated at elevated temperatures, potentially leading to intergranular crack formation and eventual creep failure (Gong et al., 2021). Creep also significantly impacts blade material fatigue strength, contributing to failure. Mudang et al., (2021) investigated the influence of heat treatment on the microstructure and creep behavior of the Fe-40Ni-24Cr alloy, commonly used in gas turbine applications. The study revealed that titanium and niobium-rich precipitates in the alloy enhance creep properties, with grain size affecting high-temperature creep behavior. The findings emphasize the role of heat treatment-induced microstructural changes in altering the creep characteristics of the Fe-40Ni-24Cr alloy. Choi et al., (2020) introduced an approach for operation-adaptive damage analysis in steam turbines, incorporating a nonlinear creep-fatigue interaction model. This method considers the adaptive selection of hyper-parameters, integration of real operational data, and the interpretation of creep-fatigue damage interaction with respect to operational modes. The results underscore that nonlinear creep and fatigue damage interaction is influenced by operational mode and the prevailing damage mechanism. This approach holds potential for accurately assessing damage in steam turbines, contributing to more effective plant operation and maintenance.

Zhang et al., (2019) present the fuzzy multi-extremum response surface method (FMERSM) for comprehensive probabilistic optimization of multi-failure/multi-component structures, with a specific focus on optimizing the probabilistic fatigue/creep coupling of a turbine bladed disk. Their research covers various optimization factors and targets, including rotor speed, temperature, creep stress, creep strain, fatigue damage, and creep damage, incorporating reliability and GH4133B fatigue/ creep damages as constraint functions. The results highlight the significance of controlling gas temperature (T) and rotor speed (ω) as primary factors in bladed disk system optimization, with notable decreases of 85 K and 113 rad/s, respectively. In another study, Zhu et al., (2019) focused on examining the detrimental effects of creep-fatigue interaction and creep rupture on a steam turbine rotor exposed to cyclic thermal-mechanical loadings, using the Linear Matching Method (LMM) and experimental creep data of FB2 heat-resistant steel. The findings underscore the dominance of creep in structural failure, surpassing the influence of fatigue behavior, with creep-induced damage exceeding that of fatigue. The analysis offers valuable insights into creep-fatigue phenomena in the steam turbine rotor under diverse loading conditions, introducing novel creep rupture curves that enhance understanding and ensure reliable functionality at elevated temperatures.

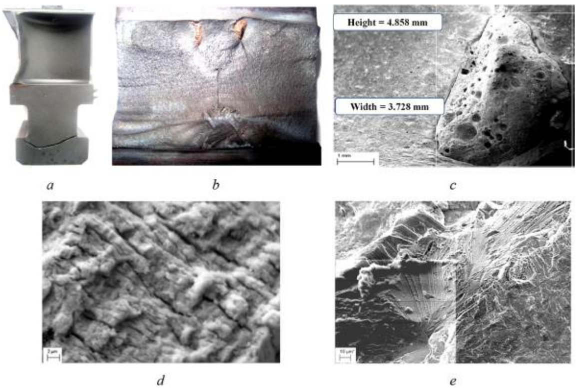

Figure 2 Macro view (a) and magnified details (b, c) of broken blades with paired shanks reveal subsurface slag inclusions along the fusion line, leading to fatigue failure signs in steel 15Kh11MF, either initiated from the slag-base metal interface (c, d) or the front of cold cracks during blade shank welding (e). Adapted from Plesiutschnig et al., (2016).

Abdollahzadeh Jamalabadi (2016) investigated the influence of heat radiation from neighboring turbine blades on the creep characteristics of a turbine blade, focusing on Moly Ascoloy within the gas turbine's operational temperature range and full-scale geometry. M-152 alloy was used for the turbine blade, a 12 Cr alloy known for high tensile strength, with the Weibull distribution modeling the probability of blade failure. Findings revealed a positive correlation between the probability of failure and rising temperature, while blade distance exhibited a negative correlation. Increasing the gap between stator blades was found to mitigate the impact of heat radiation, but further research is needed for effective preventative strategies. In another study, Wang et al., (2016) investigated the impact of temperature fluctuations on the creep-fatigue characteristics of a steam turbine rotor during operation. They observed that frequent thermal fluctuations during steady-state operation contributed significantly to creep-fatigue damage. Introducing a viscoplastic constitutive model with damage, their results indicated that temperature changes led to stress oscillations and increased creep damage compared to constant temperature conditions. This underscores the importance of considering temperature transients in steam turbine design and operation to mitigate creep-fatigue damage and ensure consistent and reliable performance.

The key relations among the studies lie in their collective exploration of creep behavior and its impact on various engineering components, such as steam turbine rotors, bladed disks, and gas turbine materials. Gong et al., (2021), and Zhang et al., (2019) delve into the effects of temperature on creep and creep-fatigue behavior, with the former focusing on temperature fluctuations in steam turbine rotors and the latter proposing a probabilistic optimization methodology for turbine bladed disks. Mudang et al., (2021) investigates the influence of heat treatment on the microstructure and creep behavior of an Fe-40Ni-24Cr alloy used in gas turbines, while Choi et al., (2020) presents a practical method for evaluating damages in steam turbines considering nonlinear creep and fatigue interactions. Overall, these studies collectively contribute to a deeper understanding of creep-related phenomena in turbine components and provide valuable insights for optimizing turbine design, operation, and maintenance to mitigate creep-induced failures and enhance the reliability of these critical engineering components.

In summary, steam turbine blade failures can be attributed to various factors, each with its unique mechanisms and challenges. Thermal stress arises from temperature gradients, while mechanical stress results from forces and pressures. Corrosion occurs due to chemical reactions, erosion from mechanical wear, fatigue from cyclic loading, and creep from time-dependent deformation under constant stress and high temperatures. Understanding and mitigating these factors is crucial for ensuring the structural integrity and reliability of steam turbine blades, thereby ensuring safe and efficient turbine operation. Table 1 compiles studies on steam turbine blade failures, highlighting the specific causes behind each failure. It offers a concise overview of the factors contributing to the blade failures and provides a comprehensive discussion of the various techniques used to address these factors. Previous research, spanning from 2016 to the latest findings in 2023, has identified five major factors: thermal stress, mechanical stress and vibration effects, corrosion, erosion, and fatigue. Each study provides valuable insights into the failure mechanisms and proposes various methodologies for damage assessment, optimization, and real-time failure diagnosis in steam turbines.

3. Selection of blade material in steam turbine

Steam turbine blade materials are pivotal in determining turbine efficiency and durability. Table 2 provides insights into various blade materials, their limitations, and applications. It lists martensitic, martensitic-aging, and austenitic-martensitic steels, detailing their chemical composition, mechanical properties, and weaknesses. The table also highlights their use in turbine blades and specific vulnerabilities like erosion susceptibility, cracking, and low-temperature performance. Referenced studies focus on different materials, using various testing methods to assess performance characteristics. Titanium alloys, showcased in research by Sherfedinov et al., (2023), and Prabhunandan, & Byregowda (2018), emerge as promising choices due to their reliability, erosion resistance, and high mechanical properties, particularly Titanium alloy Ti6Al4V. This information aids in selecting the most suitable blade material for specific steam turbine operating conditions and requirements.

On the other hand, stainless-steel compositions such as AISI 422, CA6NM, 12%Cr-steels, and 16-4 PH have been extensively studied for their corrosion resistance and mechanical properties. Kumar, & Reddy (2022) emphasize the corrosion resistance of stainless steel, while Mabruri et al., (2020) specifically point out the higher pitting corrosion resistance of CA6NM compared to wrought 410 stainless steels. Inconel alloys, especially Inconel 718, have been identified by Mukherjee et al., (2022) as potential replacements for stainless steels at higher temperatures, offering better mechanical properties and increased turbine efficiency. Fameso et al., (2022) demonstrate the successful application of Laser Shock Peening (LSP) in inducing compressive residual stresses, thereby enhancing material properties for turbine blade materials. The behavior of materials under elevated temperatures and different heat treatment regimens is investigated by Sangode (2021), and Mudang et al., (2021), shedding light on their creep strength and stability.

Furthermore, Zhang et al., (2021) conducted studies to evaluate the water droplet erosion (WDE) resistance of blade materials under specific working conditions and ranked their performance accordingly. The velocity coefficients (n) of the tested materials were in the range of 0.2-20, with the order of velocity coefficients being Ti6Al4V < 0Cr17Ni4Cu4Nb < 2Cr13 < 0Cr18Ni9. He et al., (2023) stresses the significance of fatigue and endurance strength when selecting superior blade materials, emphasizing the importance of mechanical properties. Additionally, several studies mention the influence of grain size and microstructure on mechanical properties and corrosion resistance, as discussed by Mudang et al., (2021), and Mabruri et al., (2020). Lastly, comparative analyses conducted by Kumar, & Reddy (2022), Slaston et al., (2020), and Teuber et al., (2019) provide valuable insights into the strengths and weaknesses of various materials concerning fatigue resistance, corrosion resistance, and erosion resistance.

Based on the studies mentioned, it appears that the most commonly used material for steam turbine blades is stainless steel. Several studies, such as Kumar, & Reddy (2022), Mabruri et al., (2020), and Teuber et al., (2019), have explored various stainless-steel compositions, including AISI 422, CA6NM, 12%Cr-steels, and 16-4 PH, for their suitability in turbine blade applications. Stainless steel is favored for turbine blades due to its corrosion resistance, mechanical properties, and cost-effectiveness. It offers good resistance to various corrosive agents, making it suitable for applications where exposure to steam and other chemicals is common. Additionally, stainless steel alloys exhibit favorable mechanical properties, including strength and fatigue resistance, essential for withstanding the stress and high rotational speeds experienced in steam turbines. While other materials like titanium alloys, Inconel alloys, and martensitic steels have also been investigated for turbine blades and have shown promising characteristics, stainless steel compositions appear to have received significant attention in the studies mentioned.

Materials suitable for different failure modes can be summarized as follows: Stainless steels (AISI 422, CA6NM, 12%Cr-steels, and 16-4 PH) exhibit good corrosion resistance, making them suitable for turbine blades exposed to steam and corrosive agents (Kumar, & Reddy 2022). Inconel 718 alloy, recommended for higher temperatures, offers superior high-temperature performance and creep resistance (Mukherjee et al., 2022), making it suitable for blades facing extreme temperature conditions. Martensitic steels (martensitic, martensitic-aging, and austenitic-martensitic compositions) are known for their mechanical strength and fatigue resistance, reducing the risk of mechanical failures in steam turbines (Slaston et al., 2020). Titanium alloy Ti6Al4V, as shown by Sherfedinov et al., (2023), stands out for erosion resistance, making it suitable for blades exposed to erosive forces and high-speed liquid-solid impact. However, material selection should consider the specific operating conditions and demands of each steam turbine, including factors like mechanical properties, corrosion resistance, erosion resistance, temperature performance, and cost, as materials may excel in some areas while presenting limitations in others, necessitating comprehensive material selection analyses.

4. Conclusion

This work initially introduces fundamental concepts and theories concerning the failure mechanisms and modes of failure of steam turbine blades. The study then categorizes literature into tables based on failure mechanisms, blade material composition, affected components, conducted analyses, and failure modes. It also emphasizes materials for improved steam turbine blade efficiency and reliability. Key findings are as follows:

1) Thermal and mechanical stresses, corrosion, erosion, fatigue, and creep are major contributors to steam turbine blade failures.

Thermal stress and operational fluctuations can cause deformation and cracking, while mechanical stresses intensified by dynamic forces lead to fatigue failure. Understanding creep behavior and microstructural changes is essential for assessing creep resistance.

2) Erosion is a significant factor contributing to steam turbine blade failures, evident from the studies. This results from deposits, corrosion, solid particle impact, and mechanical wear on the blade surface over time. Different types of erosion, including corrosion erosion, cavitation erosion, and erosion-corrosion, have been identified as common causes of blade damage and material loss. These erosion-related issues result in reduced turbine efficiency, increased steam consumption, and potential structural damage. Various optimization techniques, such as drainage grooves, injection of hot steam, and control of NaCl concentration, have been proposed to mitigate erosion and improve turbine performance.

3) Material selection for steam turbine blades is crucial for efficiency and durability. Stainless steels like AISI 422, CA6NM, 12%Cr-steels, and 16-4 PH are favored for commendable corrosion resistance, mechanical properties, and cost-effectiveness. Inconel 718 excels in high-temperature environments, offering superior performance and creep resistance. Martensitic steels minimize the risk of mechanical failures with their mechanical strength and fatigue resistance. Titanium alloy Ti6Al4V stands out for erosion resistance, making it suitable for blades exposed to erosive forces. Each material has specific strengths catering to different failure modes, emphasizing the need for tailored selection based on specific turbine conditions. While stainless steels are commonly used, other materials show promise in addressing unique challenges, necessitating comprehensive analyses for material selection.

Despite valuable findings, there are research gaps that exist in steam turbine blade failures and material selection. Current studies focus on specific failure mechanisms and prevention but lack consideration of the combined failure effects. Holistic approaches are needed, considering thermal and mechanical stress, corrosion, erosion, and fatigue for enhanced reliability. In material studies, gaps still persist. Long-term assessment of titanium alloys in continuous operation is crucially important. Comprehensive corrosion resistance studies for stainless steels in diverse environments and against various agents are essential. Further research on Inconel alloys under extreme conditions is necessary. Multi-factor analyses for mechanical, thermal, corrosion, and erosion resistance are vital for material selection. Comparative manufacturing studies will provide economic insights. Closing these gaps will advance material choice for improved turbine efficiency and safety in power generation.

Table 1 Studies on failure mechanisms and failure modes for steam turbine

Failure Mechanism	**Literature**	**Type of failure in steam turbine blade**	**Material composition of blade**	**Component subject to failure**	**Analyses performed/ tools**	**Failure Mode (Causes of failure)**
Thermal stress	Mukherjee et al., (2022)	Thermal stress	Inconel 718, 17-4Ph Stainless Steel	Turbine blade	• Ansys Workbench	• Centrifugal load, steam mass flow bending forces, and hot corrosion. These conditions can stress and strain blades, causing failure.
	Banaszkiewic, 2018	Thermo-mechanical fatigue	-	Impulse steam turbine rotor.	• Stress analysis • Finite element method	• Crack initiation in impulse steam turbine rotors subject to thermo-mechanical fatigue. • It identifies heat grooves as the most critical areas from the viewpoint of thermal fatigue.
Mechanical stress and Vibration effect	Benammar, & Tee (2023)	Mechanical unbalance including friction or ware, corrosion erosion, rupture of blade, thermal unbalance and evaluative unbalance	-	Blades, bearings, couplings, gearboxes, generators, and valves	• Fault Tree (FT) method and the Artificial Neural Network (ANN) method.	• Not mention
	Shukla, & Harsha (2016)	Crack due to vibration effect	X10crnimov1222	Last stage low pressure steam turbine	• FEM	• The loss of stiffness in the vicinity of blade root.
Corrosion	Puspasari et al., (2021)	Pitting corrosion	CA6NM stainless steel	Steam turbine blades	• Measured open circuit potential with Gamry Instruments G750 Series. • In 3.5% NaCl solution, do cyclic polarization test. • A JEOL Model JSM-5400 SEM • EDS	• By exposure to specific environments such as chloride or sulfide solution.

Table 1 Cont.

Failure Mechanism	Literature	Type of failure in steam turbine blade	Material composition of blade	Component subject to failure	Analyses performed/ tools	Failure Mode (Causes of failure)
Corrosion (Cont.)	Xie et al., (2020)	Transverse cracking	2Cr13 steel	Last stage blade of the low-pressure rotor in the steam turbine	• Macro morphology analysis • Scanning electron microscopy (SEM) • Microstructure analysis • Mechanical property testing • Chemical composition analysis • Energy spectrum analysis	• Caused by transverse cracking in the blade body due to the accumulation of corrosive Cl- on the leaves, which combined with tensile stress during blade operation and resulted in stress corrosion microcracks. • These microcracks extended under cyclic excitation stress during rotor rotation at high speed, leading to fatigue mode cracking. • Cracking due to stress corrosion and fatigue.
	Puspasari et al., (2021)	Pitting corrosion	CA6NM stainless steel	Steam turbine blades	• Measured open circuit potential with Gamry Instruments G750 Series. • In 3.5% NaCl solution, do cyclic polarization test. • A JEOL Model JSM-5400 SEM • EDS	• By exposure to specific environments such as chloride or sulfide solution.
	Xie et al., (2020)	Transverse cracking	2Cr13 steel	Last stage blade of the low-pressure rotor in the steam turbine	• Macro morphology analysis • Scanning electron microscopy (SEM) • Microstructure analysis • Mechanical property testing • Chemical composition analysis • Energy spectrum analysis	• Caused by transverse cracking in the blade body due to the accumulation of corrosive Cl- on the leaves, which combined with tensile stress during blade operation and resulted in stress corrosion microcracks. • These microcracks extended under cyclic excitation stress during rotor rotation at high speed, leading to fatigue mode cracking. • Cracking due to stress corrosion and fatigue.
	Kshirsagar, & Prakash (2019)	Corrosion	Stainless steel grade material	Turbine blade	• Modal and harmonic analyses	• Due to the bad working environment of steam turbines
	Adnyana (2018)	Corrosion fatigue	-	Low-pressure steam turbine blade.	• Macroscopic examination, • Chemical analysis, • metallographic examination, • Hardness testing, • SEM equipped with energy-dispersive spectroscopy analysis.	• The combined impact of cavitation erosion and fatigue.

Table 1 Cont.

Failure Mechanism	Literature	Type of failure in steam turbine blade	Material composition of blade	Component subject to failure	Analyses performed/ tools	Failure Mode (Causes of failure)
Corrosion (Cont.)	Katinić, & Kozak (2018)	Corrosion fatigue	Martensitic stainless steel Z10CD13	high pressure turbine (HPT) blades.	• FEM modeling and simulation.	• Not mention
	Plesiutschnig et al., (2016)	Corrosion	Ferritic/Martensticx20cr13	Root of third blade row LP	• Metallographic Investigation • FEA • Linear Elastic Fracture Mechanics (LEFM)	• Pitting corrosion • Centrifugal load and superimposed bending load caused by unsteady steam forces are responsible for the crack propagation.
Erosion	Hosseini et al., (2023)	Erosion and Mechanical damage	-	The last stage of the steam turbine (two-phase flow)	• TOPSIS algorithm and mathematical equations	• Erosion rate as a criterion for evaluating the drainage groove creation.
	Hosseinizadeh et al., (2023)	Erosion	-	Steam turbine blade	• Multi-objective optimization (equations and mathematical models)	• Water droplets in steam turbine blades can reduce efficiency and risk safety.
	Zhang et al., (2023)	Erosion due to excessive NaCl concentration	-	Steam turbine blade	• Mathematical equations and simulations, • non-equilibrium condensation model.	• NaCl in steam can reduce efficiency and erode turbine blades, causing safety issues and shortening maintenance cycles.
	Quintanar-Gago et al., (2021)	Droplet erosion, corrosion, cracking, and fatigue	-	Rotating blades in the low-pressure section of the steam turbine	• Bayesian network model	• Mechanical stresses
	Thijel et al., 2021	Crack and fracture due to erosion corrosion	X20Cr13 martensitic chrome alloy steel	Low-pressure last stage turbine blade of a 1.7 MW steam turbine	• Visual, mechanical, • Chemical tests.	• Erosion-corrosion pitting on the blade surface

Table 1 Cont.

Failure Mechanism	Literature	Type of failure in steam turbine blade	Material composition of blade	Component subject to failure	Analyses performed/ tools	Failure Mode (Causes of failure)
Erosion(cont.)	Yadav et al., (2018)	Erosion and breaking of the blade	-	Turbine blade	• Not mention	• Turbine blades convert steam into shaft work, but erosion and particle deposits can cause defects. • Poor quality steam can dissolve boiler salts, leading to reduced steam flow and increased axial thrust.
	Azimian, & Bart (2016)	Erosion	Stainless steel 510	Inward flow steam turbine	• CFD simulations (ANSYS CFX 15.0)	• Ingested steam flow containing solid particles
Fatigue	Krechkovska et al., (2023)	Fatigue fracture	High-alloyed heat-resistant steel 15Kh11MF	Steam turbine rotor blades. (HPT and LPT)	• Standard mechanical testing • Resistance to FCG • Metallography • Fractography • SEM EVO-40XVP.	• Technical problems include blade edge corrosion, uneven microstructure, and surface layer micro damages from poor welding and/or hardening. • The corrosive impact of steam-water combination in the phase transition zone adds to fractures.
	He et al., (2023)	Fatigue fracture due to excessive content of banded δ ferrite and corrosion pits	12Cr12Mo, martensitic heat-resistant stainless steel	Fourth blade of the low-pressure steam turbine unit in a power plant	• OLM • SEM • EDS • Room temperature tensile test • Charpy impact test, • EDS energy spectrum analysis	• High banded δ ferrite content reduces fatigue and endurance strength, resulting in blade performance that does not fulfill usage requirements. • Improper heat treatment or forging temperature management causes excessive δ ferrite in the fracture blade. • The failing turbine blade's macroscopic inspection revealed a fracture in the center and corrosion sites on the surface.
	Kumar et al., (2020)	Fatigue due to thermal, mechanical and chemical influence	Super alloys	Turbine blades	• Thermal analysis (Ansys software) • Blade design CATIA software	• Thermal influence, mechanical influence, or chemical influence.
	Cano et al., (2019)	Fatigue and Crack initiation	Stainless steel AISI 410	Blades of the last stage (L-0) from a 110 MW output steam turbine	• Rotating bending fatigue testing machine • Numerical and analytical models	• Low cycle fatigue and strain cycling fatigue, which can cause structural deterioration and lead to failure • Centrifugal forces acting on the blades can contribute to the initiation and propagation of cracks.

Table 1 Cont.

Fatigue (cont.)	Tian et al., (2019)	Mechanical fatigue fracture and corrosion fatigue fracture	-	Steam turbine blade	• Non-Destructive Testing techniques.	• The reason for the cracking and fracture of steam turbine blade is corrosion fatigue fracture. • The fatigue crack originals are the pitting holes on the blade surface.
	Bhagi et al., (2018)	Fatigue	AISI420	L-1 low pressure steam turbine blade	• Mathematical modeling, • Finite element modeling, • Three-dimensional scanning technique, • ANSYS software.	• High dynamic stresses, which produce high cycle fatigue.
Creep	Mudang et al., (2021)	Creep	Fe-40Ni-24Cr alloy	Not provide	• X-ray diffraction (XRD) analysis • Matsuzawa-DVK II series Vickers Hardness Tester • Diamond pyramid • Energy-dispersive X-ray spectroscopy (EDX) • Elemental mapping analysis • Transmission electron microscopy (TEM) examination	• Creep is a time-dependent deformation that occurs under constant load or stress at high temperatures, and it is a principal failure mechanism for components operating at elevated temperatures. • Creep rupture in Fe-Ni-Cr alloy is characterized by the formation of intergranular cavities and intergranular wedge cracks, resulting from long-term exposure to high temperature and pressure conditions, leading to materials' failure.
	Choi et al., (2020)	Creep and Fatigue damage	-	Critical components of steam turbines	• Nonlinear creep-fatigue interaction model. • Statistical methods,	• Not mention
	Zhang et al., (2019)	Creep fatigue	-	Turbine bladed disks	• Fuzzy multi-extremum response surface method (FMERSM)	• Due to fatigue and creep.
	Zhu et al., (2019)	Creep fatigue and creep rapture	FB2 heat-resistant steel,	Steam turbine rotor.	• Numerical method • Linear Matching Method (LMM)	• The main cause of steam turbine rotor failure during long-term high-temperature operation is creep.
	Abdollahzadeh Jamalabadi (2016)	Creep	M-152 alloy, (12Cr alloy)	Turbine blades	• Numerical assessments (software COMSOL)	• Not mention
	Wang et al., (2016)	Creep-fatigue damage	Not mention	Steam turbine rotor	• Viscoplastic constitutive model • Thermo-mechanical FE analysis • CNOW model in a UMAT subroutine • FEM • Material modeling software.	• Frequent thermal fluctuations during the steady-state operation phase as one of the most influential factors.

Table 2 Studies on various selections of steam turbine blade materials with their limitations and applications

Material Used	Superior Material	Analysis Performed	Research conclusion	Limitations	Applications	Literature
TC-5 titanium alloy and titanium alloy Ti6Al4V	Titanium alloy Ti6Al4V	• Stress and vibration analysis	• To modernize long-term operated high power steam turbines at cheap cost, it is necessary to integrate contemporary advancements with existing power plants and establish crucial scientific and technological techniques. • Titanium alloy is a promising choice for the blades of the low-pressure cylinder of powerful steam turbines, since it offers better dependability, erosion resistance, and wear resistance than TC-5 titanium alloy utilized in existing turbines. • The stress and vibration characteristics of the new blades in the last stage of the low-pressure cylinder meet technical criteria.	• Presented work is a case study of the design of titanium alloy working blades of the last stage of the low-pressure cylinder of powerful steam turbines conducted by a single enterprise. Therefore, the results may not be generalizable to other types of turbines or other manufacturing companies. • The paper does not provide a comparative analysis of the performance of the new blades with the blades made of other materials or designs.	• This study presents research on developing titanium alloy working blades for the final stage of low-pressure cylinders in powerful steam turbines. • Stress and vibration analysis of new blades can ensure safe and long-term operation of modernized turbines. • This research can be utilized to modernize power installations at minimal cost for long-term operation. • The research can enhance the efficiency and reliability of steam turbines, which are commonly employed in power generation.	Sherfedinov et al., (2023)
12Cr12Mo, martensitic heat-resistant stainless steel	Superior blade material should have a lower content of banded δ-ferrite to ensure better fatigue and endurance strength.	• Optical light microscope (OLM), • SEM • Room temperature tensile test and Charpy impact test, • EDS energy spectrum analysis	• The premature failure of the fourth blade of the low-pressure turbine unit in a power plant was caused by the excessive content of banded δ-ferrite in the blade, which led to a decrease in its fatigue strength and endurance strength. • The consistency between crack propagation direction and banded δ-ferrite direction further promotes crack initiation and prolongation,	• Study focuses on the failure analysis of a single steam turbine blade in a specific power plant, and the findings may not be generalizable to other types of steam turbines or power plants. • Does not provide information on the cost-effectiveness of the proposed prevention and improvement measures.	• Discuss failure analysis of steam turbine blades, including material faults, fatigue, corrosion, and mechanical damage. • This study can help power plant operators and maintenance workers detect blade failure reasons, reduce shutdowns, and increase steam turbine dependability and safety. • The research recommends tight forging temperature and heat treatment management to decrease material defects and improve blade mechanical properties.	He et al., (2023)

Table 2 Cont.

Material Used	Superior Material	Analysis Performed	Research conclusion	Limitations	Applications	Literature
Stainless steel, Titanium alloy, and Aluminum alloy,	Titanium alloy	• Structural & Thermal Analysis	• The behavior of stainless steel, titanium alloy, and aluminum alloy is examined in high-stress zones. • Stainless steel is the greatest material for corrosion resistance. • Titanium alloy is the most suitable of the three compositions. • Frequent mechanical breakage of turbine blades is common in turbines. • To prevent failures, choose a material that can withstand mechanical and thermal loads.	• The analysis was performed under specific operating conditions and may not be applicable to all scenarios. • The study only considered three materials, and there may be other materials that could be more suitable for turbine blade construction.	• Designing and analysis of turbine blade structures. • The findings of the study can be used to select appropriate materials for turbine blade construction based on their ability to resist mechanical and thermal loads. • The finite element analysis method used in this study can also be applied to other engineering problems that involve stress and deformation analysis.	Kumar, & Reddy (2022)
Chromium-based steel alloyed	Not mention	• Numerical analysis by Commercial finite element code ABAQUS	• Laser shock peening achieves up to 700 MPa peak compressive residual stresses in Chromium-based steel alloyed turbine blade material. • Adjusting LSP process parameters enhances CRS in the treated material, with laser shock intensity being the most influential, followed by exposure time, shot size, overlaps, and shot impact angle. • The research presents a validated LSP simulation model that predicts residual stress patterns and the effects of varying input parameters on laser-induced residual stress.	• Study specific to LSP for enhancing residual stresses in Chromium-based steel turbine blades, not generalizable to other materials or components. • Focuses on linear input parameter adjustments, not accounting for non-linear variations. • Suggests experimental validation of numerical models before practical application.	• The study has practical implications for power generating equipment, specifically enhancing residual stresses in Chromium-based steel alloyed turbine blades. • The study's findings can optimize laser shock peening (LSP) for condition-based maintenance and health monitoring. • The study's numerical, experimentally verified LSP simulation model can predict the material's residual stress regime.	Fameso et al., (2022)
Inconel 718 and 17-4Ph Stainless Steel	Inconel 718	• Performs stress and thermal analysis	• Inconel 718 alloy may be a viable alternative to stainless steels for longer blades at high temperatures, as it retains mechanical qualities under harsh circumstances, reducing blade failures and increasing turbine efficiency.	• The study was conducted under controlled laboratory conditions, and the results may differ in real-world scenarios. • The study only focused on two materials.	• The findings can be applied in the design and manufacturing of steam turbine blades for high-temperature applications, such as aircraft engines, gas turbine engines, refrigerant tankage, and cryogenic tankage.	Mukherjee et al., (2022)

Table 2 Cont.

Material Used	Superior Material	Analysis Performed	Research conclusion	Limitations	Applications	Literature
X22CrMoV121, Haste alloy, stainless steel, and Inconel 600	X22CrMoV121	• Parameter variation and evaluation • 3D modeling using CATIA software • Static and thermal analysis using ANSYS software • Modal analysis and Campbell diagram plotting • Harmonic analysis • Stress analysis	• The authors recommend X22CrMoV121 for steam turbine blades due to its creep strength, creep-fatigue resistance, notch sensitivity, and damping qualities. • The authors do not assert that X22CrMoV121 is preferable to other materials for a certain steam turbine blade design, as appropriateness relies on several aspects. • Conducted modal and harmonic analysis for the rotating cantilever beam, suggesting improvements to the turbine designer for unlimited blade life. • The blade design meets theoretical fatigue life requirements, however finite element analysis is problematic. • Theoretically, the blade model has an infinite life (2.438e6), but ANSYS software yields only 86436 cycles as fatigue life for the current design.	• The analysis pertains to a specific steam turbine blade design and may not apply to other designs or applications. • The authors narrowly focus on three materials for the steam turbine blade, excluding potential alternatives or combinations. • The report lacks a full cost analysis for each material, which could be crucial for choosing a material for a steam turbine blade. • The lack of experimental validation in the analysis may reduce the reliability of the conclusions.	• Can be useful for researchers and engineers working in the field of steam turbine design and analysis. • Provides insights into the design and analysis of steam turbine blades, including the use of 3D modeling software and finite element analysis to evaluate the stress, deformation, and thermal behavior of the blade under static-thermal load conditions. • The paper also compares the analysis results for three different materials for the steam turbine blade, which can be helpful in selecting a suitable material for a specific steam turbine blade design. • The paper can contribute to the development of more efficient and reliable steam turbine systems	Sangode (2021)
Fe-40Ni-24Cr alloy	Not mention	• Electron Backscatter Diffraction (EBSD) analysis • SEM • XRD analysis • Matsuzawa-DVK II series Vickers Hardness Tester • Diamond pyramid indenter • EDX • TEM	• Heat treatment regime considerably impacts Fe-40Ni-24Cr alloy microstructure development and creep behavior. • The alloy's creep qualities improved by raising the temperature from 800 to 900 °C, according to the study. • Minimum steady-state creep strain rate for Fe-40Ni-24Cr at 800°C and 900°C increases by 5% and 1%, respectively, with grain size. • Microstructural development showed that grain boundaries functioned as both dislocation sources and mobility obstacles. • The study discovered that grain size significantly impacts high-temperature creep characteristics of alloys.	• The study examined the impact of heat treatment on the microstructure and creep behavior of Fe-40Ni-24Cr alloy at 800°C and 900°C, with a constant applied stress of 100 MPa. • The study may not apply to different temperatures or stress conditions, as it only examined the impact of heat treatment on one alloy.	• Useful for materials science and engineering researchers, especially those developing high-temperature alloys for gas and steam turbines. • The study offers insights into Fe-40Ni-24Cr alloy microstructure evolution and creep behavior under various heat treatment conditions, enabling optimization of mechanical attributes and performance. • This study can also help choose Fe-40Ni-24Cr alloy heat treatment regimens for desirable microstructure and creep behavior.	Mudang et al., (2021)

Table 2 Cont.

Material Used	Superior Material	Analysis Performed	Research conclusion	Limitations	Applications	Literature
CA6NM stainless steel with varying molybdenum and nitrogen content. samples with an addition of 1 % Mo, 2 % Mo, and 2 % Mo-1 % N.	Modified cast CA6NM stainless steel in 3.5% NaCl solution.	• Open circuit potential measurement • Cyclic polarization test • SEM analysis • Energy-dispersive X-ray spectroscopy (EDS).	• Evaluated the effect of tempering on pitting corrosion resistance in 3.5% NaCl for cast modified CA6NM stainless steel. • In open circuit potential measurements, double-tempered CA6NM was shown to be nobler and less reactive than single-tempered. • Sample CA6NM with 2%Mo-1% N and -9.5 mV twice tempered treatment showed the highest free corrosion potential. • The cyclic polarization test revealed that adding molybdenum and nitrogen enhanced the E pit value of CA6NM samples, except for CA6NM3 with double tempering. Nitrogen-containing CA6NM should not be double-tempered.	• The experiments were conducted only in a 3.5% NaCl solution, which may not represent all the possible environments where the modified cast CA6NM stainless steel could be used. Therefore, the results of this study may not be directly applicable to other environments. • Does not provide a comprehensive comparison of the modified cast CA6NM stainless steel with other materials in terms of pitting corrosion resistance.	• Provide insights into the effect of tempering treatment on pitting corrosion resistance of modified cast CA6NM stainless steel in a 3.5% NaCl solution. • Useful for designing and selecting materials for steam turbine blade applications in chloride environments. • The addition of Mo and N as chemical alloying elements could improve the corrosion resistance of the modified cast CA6NM stainless steel.	Puspasari et al., (2021)
STS 422:12 Cr Steel, and AISI 422	Not mention	• Material properties analysis, • Stress analysis of L-1 by the finite element analysis software	• The breakdown of the L-1 blade of a 220 MW steam turbine was explored. • The crack population was more prevalent at L-1 Gen than L-0 Gov and L-1 Gov. • Cracks were mostly 300-400 mm from the blade root and not related to pitting defects. • The fundamental cause of L-1 blade failure was examined using a three-stage analytical approach. • The finite element study revealed that the inaccurate shroud gap caused greatest stress at 300-400 mm from the root area of the L-1 blade span.	• The study only focuses on the failure investigation and crack propagation analysis of a single LP Blade Steam Turbine 220 MW. Therefore, the findings and conclusions of the study may not be generalizable to other steam turbines or blade designs. • The study only considers a limited number of factors that may contribute to blade failure, and there may be other factors that were not considered in the analysis	• The study found that inappropriate shroud spacing, and insufficient hardness-strength material contribute to blade failure. Turbine builders and operators can reduce blade failure and increase lifespan by addressing these issues. • The research's methodologies, such as airfoil and blade dimension capture, material properties analysis, and stress analysis utilizing finite element analysis software, can analyze failure and enhance steam turbine blade design and maintenance.	Damanik, & Dahlan (2021)

Table 2 Cont.

Material Used	Superior Material	Analysis Performed	Research conclusion	Limitations	Applications	Literature
Stainless steel 2Cr13, 0Cr18Ni9, 0Cr17Ni4Cu4Nb, and titanium alloy Ti6Al4V	Not mention	• Experimental testing, data processing methods in ASTM-G73, and SEM morphology analysis	• The study examines how target surface roughness, impact angle, and velocity affect WDE properties of blade materials under various working conditions. • Analyzed velocity coefficients (n) of testing materials during high-speed liquid-solid collision. • Maximum erosion rate (ER max) is measured to quantify WDE resistance of testing materials. • SEM morphology of erosion section and hardness distribution at impact position are used to study material failure characteristics and shallow layer hardness (SLH) at three typical moments for varied WDE periods. • The studied materials have velocity coefficients (n) ranging from 0.2 to 20 with Ti6Al4V < 0Cr17Ni4Cu4Nb < 2Cr13 < 0Cr18Ni9. This study cannot establish the optimal material for steam turbine blades since WDE resistance and mechanical qualities are complex. Future research is needed to determine the relationship between WDE resistance and mechanical properties.	• The study only investigates the WDE characteristics of four blade materials under specific working conditions. Therefore, the results may not be applicable to other materials or different working conditions. • The study only focuses on the WDE resistance of blade materials and does not consider other factors that may affect the performance of steam turbine blades, such as fatigue, creep, and corrosion. • The paper does not provide a detailed discussion of the economic and practical aspects of using different blade materials in steam turbines.	• The study investigates the water droplet erosion characteristics of four blade materials under different high-speed liquid-solid impingement conditions. • The research results can provide reference data and technical support for the structure design and material selection of steam turbine blades. • Provide a better understanding of the WDE resistance of different blade materials under high-speed liquid-solid impact conditions. Therefore, the paper can be useful for researchers and engineers who are involved in the material selection of steam turbine blades. • The results of this study can be applied to the design and development of new steam turbine blades that are more resistant to water droplet erosion.	Zhang et al., (2021)

Table 2 Cont.

Material Used	Superior Material	Analysis Performed	Research conclusion	Limitations	Applications	Literature
Martensitic, Martensitic-aging and Austenitic-martensitic steels 15H11MF, 13H11H2B2MFSh, EP-410USH, EP-678BD, EP-310SH	Not specific	• Not mention	• The study analyzed the criteria and technical requirements for the working blades of the latter stages of low-pressure cylinders (LPC) in high-power steam turbines. • The paper recommends using martensitic, martensitic-aging, and austenitic-martensitic steels (15H11MF, 13H11N2Ò2MFSh, EP-410USH, EP-678BD, EP-310SH) as the main material for the production of working blades in the final stages of the LPC, based on operating conditions analysis. • Arrangement of these materials increases fatigue strength, brittleness resistance, and erosion-corrosion resistance: 15H11MF, 13H11N2Ò2MFSh, EP-410USHEP-678VD, EP-310SH.	• This review and analysis focus on the technical requirements for materials in the working blades of the latter stages of low-pressure cylinders (LPC) in high-power steam turbines, rather than experimental research. • Selecting materials for steam turbine blades is a difficult procedure that involves considering operating circumstances, material attributes, and manufacturability. • Steam turbine performance and dependability require more study and development.	• The study analyzes and selects steels for the working blades of low-pressure cylinders (LPC) in high-power steam turbines. • Examines working blade materials and steel grades for low-pressure cylinder blades, per technical specifications. • This study can increase steam turbine performance and reliability by improving design and manufacturing. • The paper's ideas for working blade materials with long active parts and research avenues can inform future study in this area.	Slaston et al., (2020)
Cast CA6NM and Wrought 410 stainless steel alloys	Not mention	• Cyclic polarization measurements for all samples • Microstructure observation by scanning electron microscope (SEM) • Hardness testing (Rockwell C) on the samples from heat-treated steels.	• CA6NM stainless steel exhibits higher pitting corrosion resistance than wrought 410 stainless steels in both simulated geothermal and 3.5% NaCl solutions. However, SEM photos reveal that CA6NM steel has more pits than 410 steels. • Adding CO2 enhances pitting potentials in simulated geothermal solution. Both steels exhibit larger and deeper pits in 3.5% NaCl compared to the simulated geothermal solution. CA6NM steel has a martensitic microstructure with smaller martensite size and higher percentage. • While metal carbides are present in both steels, their sizes and distribution are difficult to identify due to limits in optical microscope resolution and magnification. • The absence of delta ferrite in both steels is due to the lack of Mo in 410 steel and high Ni in CA6NM steel, which inhibits its production.	• The cyclic polarization measurements were conducted at room temperature, whereas the actual operating conditions of steam turbines involve high temperatures and pressures. Therefore, the results obtained from this study may not fully represent the behavior of the materials under actual operating conditions. • The study only investigated the pitting corrosion resistance of two specific types of stainless steel in certain environments, and the results may not be applicable to other materials or environments.	• The findings of this study can be useful for the selection of appropriate materials for power generation steam turbine blades, particularly in the last row of low-pressure blading. • The study provides insights into the pitting corrosion resistance of two types of stainless steel in simulated geothermal and 3.5% NaCl solutions, which are common environments in power generation. • The results can aid in the development of more corrosion-resistant materials for use in steam turbines, which can improve their reliability and reduce the risk of blade failure.	Mabruri et al., (2020)

Table 2 Cont.

Material Used	Superior Material	Analysis Performed	Research conclusion	Limitations	Applications	Literature
Stainless steel, Titanium alloy, and Aluminum alloy,	Not mention	• Thermal analysis (Ansys software)	• The results show that the temperature has a significant effect on the thermal stresses induced in the turbine blade of different alloys	• The study only analyzes the thermal stresses induced in the turbine blade under steady-state conditions and does not consider any dynamic effects. • The study only considers three different materials for the turbine blade and does not analyze other materials.	• The study provides insights into the thermal stresses induced in turbine blades made of different materials, which can be useful in designing and optimizing turbine blades for better performance and durability. • The findings of the study can be applied in the maintenance, repair, and overhaul (MRO) of engines, particularly in the regeneration of compressor and turbine blades and vanes.	Kumar et al., (2020)
Titanium alloys and Steels	AISI 422 (martensitic stainless steel)	• Vibrational analysis of the moving blade using ANSYS software.	• Improved blade design, resisting stresses, corrosive agents, and creep-inducing temperatures, increases turbine efficiency, reduces fuel consumption, and lowers operating costs. • Implement robust turbine blades, designed with advanced material technologies, to withstand extreme conditions.	• • The study focuses on a specific component of steam turbine blade design, not all factors affecting performance and efficiency. • The study investigates a few materials and designs; hence its results may not apply to other steam turbine applications.	• The evaluation of the effectiveness of certain titanium alloys and steels in resisting creep and fracture in turbine blades. • The paper compares and contrasts the aerodynamic designs of these two types of blades and their effect on turbine efficiency.	Kumaraswamy, & Raju (2019)
Steels within the strength class YS0.2 ~ 1,200 MPa: PH 12-10 Mo and PH 13-8 Mo, 12%Cr-steels and 16-4 PH.	PH12-10 steel	• Screening tests of alternative precipitation-hardening (PH) steels • Salt spray tests	• The development of a new high-strength steel for low pressure steam turbine end-stage blades is necessary to increase the efficiency of the turbine and to realize cost-efficient single flow exhaust applications. • The new blade steel had improved mechanical properties compared to commonly used 12%Cr-steels, and had good resistance to corrosion in salt spray tests. • The pitting corrosion resistance of the new blade material in aerated chloride containing solutions was found to be comparable to the established blade material 16-4 PH.	• Developed and tested high-strength steel for low-pressure steam turbine blades, including screening alternative PH steels, assessing stress corrosion cracking resistance in NaCl solutions, and salt spray testing in a climatic chamber. • Research is needed to thoroughly evaluate the performance of the new blade material in real-world turbine applications, as the results may not apply to other materials or components.	• The application of this research paper is in the development of a new high-strength steel for low pressure steam turbine end-stage blades. • The results of the study may be useful for turbine manufacturers and researchers in the field of materials science and engineering who are interested in developing more efficient and cost-effective turbine components.	Teuber et al., (2019)

Table 2 Cont.

Material Used	Superior Material	Analysis Performed	Research conclusion	Limitations	Applications	Literature
Titanium alloy	Titanium alloy	• Static stress analysis • Dynamic analysis with FEA package • ANSYS software for numerical analysis	• Utilizing ANSYS for finite element analysis is crucial in assessing the life cycle of steam turbines, enhancing their design and maintenance strategies. • Recommends the use of titanium alloy for turbine blades, given its exceptional mechanical properties, while emphasizing the importance of running the turbine assembly below critical speed to prevent potential failures.	• The analysis in the paper relies on simplifications and assumptions, potentially missing real-world complexities of steam turbine systems. • The lack of experimental validation for ANSYS-based numerical results necessitates cautious interpretation, highlighting the need for further research to validate the findings.	• The paper uses ANSYS for finite element analysis of steam turbine blades and rotors, providing insights into stress, fatigue, and rotor dynamics for turbine design and maintenance. • Valuable for material science researchers and engineers, especially in the context of titanium alloy blade discussions. Relevant to power generation, particularly in steam turbine design and maintenance.	Prabhunandan, & Byregowda (2018)

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