Review Article

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Unveiling the crucial factors and coating mitigation of solid particle erosion in steam turbine blade failures: A review

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Abstract: Steam turbines are essential for energy conversion, with blades engineered for optimal efficiency, endurance, and robustness in varying pressure conditions. However, these blades face significant risks from fatigue, corrosion, and solid particle erosion (SPE), particularly in high-pressure areas. Understanding SPE mechanisms, influenced by particle characteristics, impact angles, and material properties, is vital for developing effective mitigation strategies. From 2013 to 2023, the number of publications in this field increased by 133%, reflecting substantial growth in research. Initially, experiment-based studies represented about 30% of the research from 2013 to 2015, while simulation and computational methods became predominant, constituting approximately 70% of studies from 2020 to 2023. Key focuses included impingement angle and impact speed. Thermal spray processes dominated coating studies, comprising about 50% of research from 2014 to 2023, with physical vapor deposition at roughly 30%. Advanced coatings, like yttria-stabilized zirconia and titanium aluminum nitride, showed promise in enhancing erosion resistance. Future research should prioritize optimizing these parameters and exploring eco-friendly materials to improve turbine longevity and performance.

Keywords: erosive, steam turbine blade, solid particle erosion, coating, failure, prevention

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1 Introduction

Steam turbines are essential energy converters in thermal power plants and various industrial applications. They play a crucial role in absorbing the power of steam and converting it into mechanical energy. The turbines are equipped with comprehensively built blades that are divided into low-pressure (LP), medium-pressure (MP), and high-pressure (HP) parts as shown in Figure 1. These sections are specifically engineered to handle different operational requirements based on the varied pressures and temperatures [1]. In the LP section of the steam turbine blades, the design focuses on maximizing efficiency and extracting as much energy from the steam as possible. In the mid section (MP) of the steam turbine blades, the design aims to balance efficiency and durability, as this section experiences relatively HPs and high temperatures. Finally, in the HP section of the steam turbine blades, the design prioritizes strength and resistance to erosion and corrosion, as this section is subjected to the highest pressures and temperatures in the turbine [2]. Every section of the turbine is meticulously designed to achieve the optimal balance between efficiency, durability, and strength, so maximizing its performance.

Among the various difficulties that pose a threat to steam turbine blades, such as fatigue, corrosion, erosion, creep, and thermal stresses, erosion is particularly insidious. The continuous and unrelenting impact of water droplets or solid particles gradually erodes the surfaces of the blades, posing a risk to both the efficiency of airflow and the structural strength. Unlike slower-paced failure mechanisms, erosion accelerates the degradation process, especially in environments rich in moisture or particulate matter. Erosion in steam turbine blades occurs in two main forms: water droplet erosion (WDE) [3], which mostly affects the LP region, and solid particle erosion (SPE), which is a significant concern in HP parts [4]. The erosive effect of solid particles, such as grit or sand transported by the flow of steam, gradually wears away the surfaces of the

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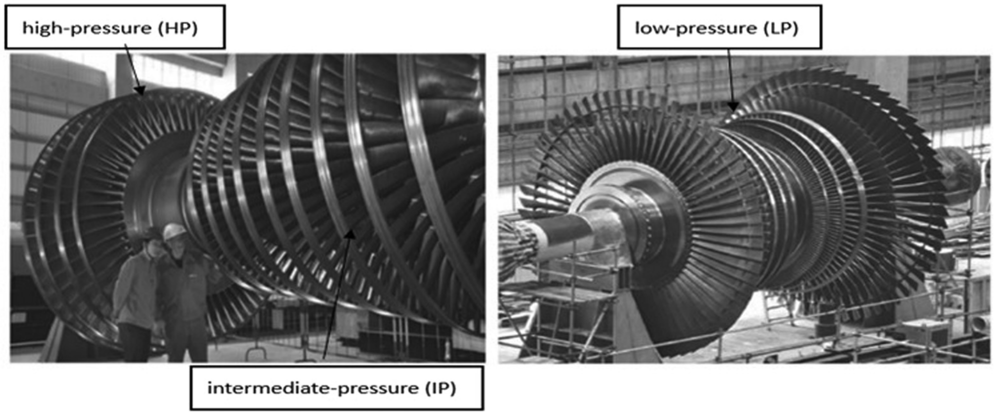

Figure 1: Rotor of the combined HP-IP and LP sections of a large impulse-type steam. Reproduced from Dick [9].

blades, often resulting in early failure [5]. To address a critical need, there are ongoing research efforts to investigate various materials, coatings, and design alterations that can improve the durability of turbine blades against erosion and corrosion [6–8].

A lot of recent research shows that SPE is a big problem for steam turbine blades. The Scopus database reveals a significant corpus of 2,806 papers (2013–2023) dedicated to this subject (Figure 2). However, despite this substantial body of literature, there remains a notable dearth of up-to-date review articles addressing SPE and its implications for steam turbine blade integrity, particularly concerning protective coating strategies. To better illustrate the methodology used in gathering and analyzing this literature, we present Figure 3, which outlines the systematic approach we followed in our review.

In light of this gap in comprehensive reviews, this article aims to address the deficiency by providing a comprehensive overview of SPE-induced failures in steam turbine blades. Section 2 delves into a thorough review of failures in steam turbine blades, while Section 3 focuses on SPE in these blades. Section 4 examines the myriad parameters influencing SPE, including particle properties

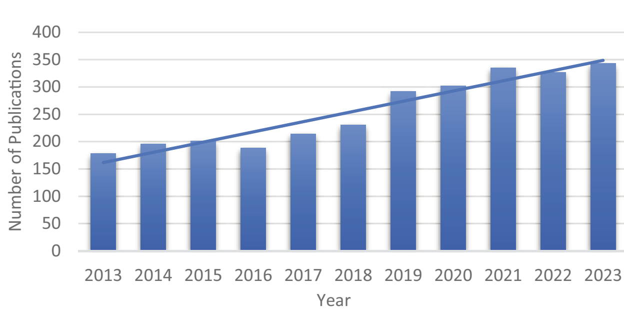

Figure 2: Number of publications for SPE between 2013 and 2023 based on Elsevier database.

and impingement conditions. In Section 5, the article scrutinizes materials and protective coatings designed to mitigate SPE, offering detailed insights into their selection and application methods. Section 6 summarizes and discusses the findings from the review. By meticulously dissecting these aspects, this review aims to bridge the existing knowledge gap and shed light on the profound impact of SPE on steam turbine blade performance. Finally, in Section 7, we conclude by identifying the current gaps in understanding and addressing the ramifications of SPE, paving the way for future research endeavors and advancements in turbine blade technology.

2 Failure in steam turbine blade

The blades of steam turbines might fail for a variety of reasons, even though they are essential parts of many industrial applications. The factors that contribute to the degradation of the system include thermal stress, mechanical stress, vibration effects, corrosion, erosion, fatigue, and creep, as shown in Figure 4. Gaining a comprehensive understanding of the complex mechanisms responsible for these failures is crucial to develop efficient mitigation techniques that guarantee consistent turbine performance across time.

Thermal stresses arise due to variations in temperature within turbine parts, resulting in deformation, cracking, and other types of damage. The studies conducted by Kumar and Reddy [10], Azeez [11], and Mukherjee *et al.* [12] have examined topics such as high-temperature low-cycle fatigue and material characteristics that are important for withstanding thermal stress. The combination of mechanical stress, fluctuating dynamic stresses, and centrifugal forces plays a crucial role in causing blade fatigue and eventual failure. The

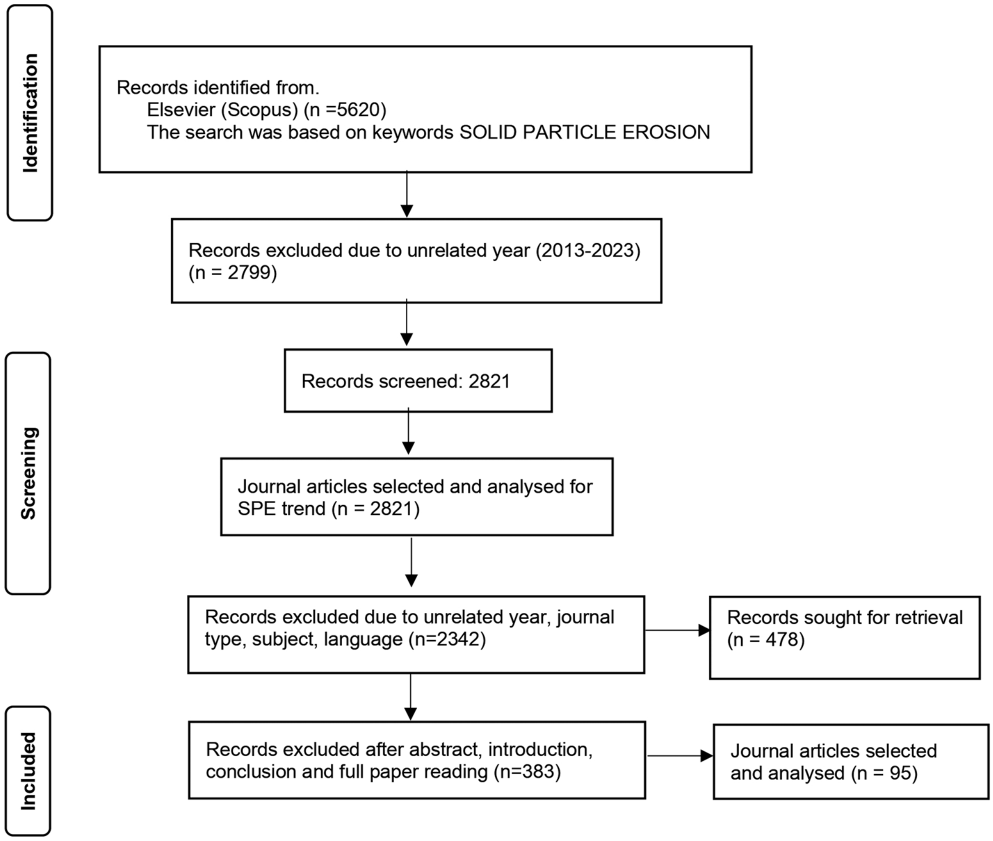

Figure 3: The flowchart of literature used for the trend on SPE.

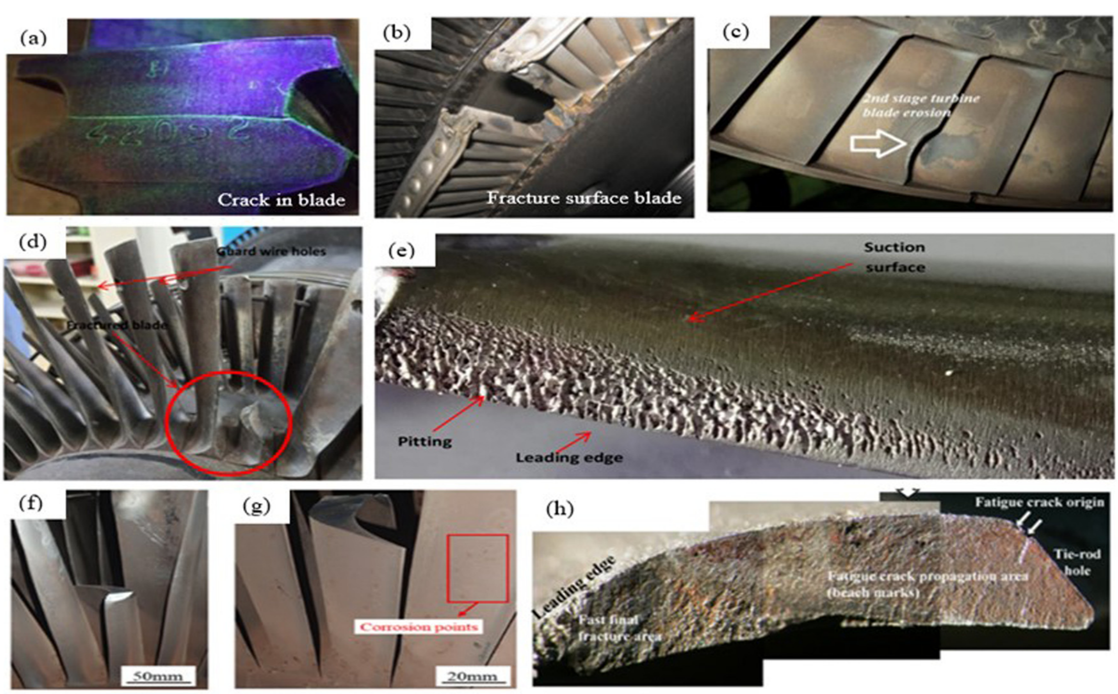

Figure 4: Common failure modes in steam turbine blades are depicted: (a) crack localization on last stage LP turbine blades, (b) fracture surface of rotor blade, (c) erosion on HP turbine rotor blade, (d) fractured blade failure in LP last stage, (e) pitting along the leading edge of turbine blade, (f and g) corrosion and fracture on blade surface, and (h) fracture surface of cracked steam turbine blade. Reproduced from [14–19].

blade experiences mechanical stresses due to the combined effects of steam pressure, steam temperature, and centrifugal forces caused by rotating movement [13].

Corrosion is a notable risk in steam turbines due to their frequent use of fuels that contain corrosive substances, including sulfur, vanadium, lead, sodium, and other elements [20]. When air or saltwater impurities are present, the presence of these chemicals can cause the formation of alkali metals. These alkali metals then launch highly destructive corrosion attacks on turbine blades, ultimately resulting in failure [21]. The study conducted by Plesiutschnig *et al.* [22] examined a crack located at the base of the third row of blades in an LP steam turbine. The steam turbine blade was made of Ferritic/Martensitic x20cr13 alloy. The researchers noted that corrosion pits at the root caused stress levels to exceed the yield stress. The primary factor leading to the onset of fatigue cracks was determined to be pitting corrosion. Additionally, crack propagation was attributed to the combined effects of centrifugal load and superimposed bending strain resulting from unstable steam forces.

Fatigue failure, a common reason for blade malfunction, happens when cyclic stresses exceed the fracture toughness of the material. Cano *et al.* [23] He *et al.* [18], and Zhao *et al.* [24] have conducted research to enhance turbine dependability by investigating the fatigue behavior. They have taken into account several elements including material qualities and operating conditions. Krechkovska *et al.* [25] examined the fatigue fracture of steam turbine rotor blades made of high-alloyed heat-resistant steel 15Kh11MF. The researchers discovered several factors that contribute to early failure, such as severe corrosion-erosion wear, uneven microstructure, and the presence of micro defects in the surface layers. The corrosive impact of the steam-water combination in the phase transition region was also discovered to contribute to the fracture process. The study examined the structural and mechanical condition of various high-alloyed heat-resistant steels in steam turbine rotor blades at different points throughout their operation.

Creep, which refers to the gradual distortion of a material over time when exposed to high temperatures and steady stress, presents an ongoing risk to the integrity of turbines. Gong *et al.* [26], Mudang *et al.* [27], and Abdollahzadeh Jamalabadi [28] have conducted research on many elements of creep behavior, such as the impact of heat treatment and material microstructure.

Erosion stands out prominently among the mechanisms affecting steam turbine blades due to its high occurrence rate, as shown in Figure 5. Its impact is particularly pronounced when compared to other common degradation mechanisms such as creep, fatigue, corrosion, thermal

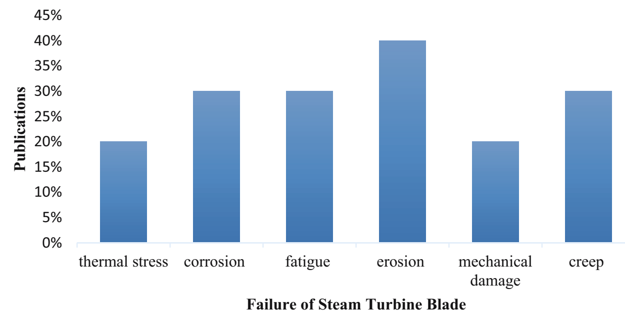

Figure 5: Distribution of type failure in steam turbine blade from 2013 to 2023.

stress, and mechanical damage. The evidence is clear from published research and industry data, where erosion consistently emerges as a leading cause of degradation in steam turbine blades. This phenomenon is often attributed to the abrasive action of particles suspended in the steam flow, which can wear away the surface of the blades over time. Erosion, which includes the effects of solid particle impact, corrosion, and mechanical degradation, gradually deteriorates the surfaces of the blades and undermines their performance [29]. Yadav *et al.* [21] and Thijel *et al.* [17] emphasize the harmful impact of erosion corrosion on the lifespan and performance of blades and recommend taking proactive maintenance and optimization steps. Thijel *et al.* [17] examined a fracture in an LP steam turbine blade at an Iraqi refinery. They concluded that the fracture was mainly caused by erosion–corrosion pitting and a decrease in material strength. The study conducted by Yadav *et al.* [21] investigated the effects of foreign particles on several turbine components, specifically blades. They emphasized that turbine blades play a vital role in turning steam into shaft work. However, erosion and particle deposits can cause defects, resulting in operational problems such as reduced steam flow and increased axial thrust. These issues arise from the poor quality of steam caused by the dissolving of boiler salt.

WDE, alongside SPE, significantly damages steam turbine blades, often leading to critical material loss, particularly on the leading edges, which exhibit rough, eroded surfaces characteristic of WDE, as shown in Figure 3(e). WDE commonly affects LP and MP steam turbine blades, where wet steam conditions result in frequent high-velocity water droplet impacts [30]. The erosion severity increases with larger droplets and higher velocities, following a power-law relationship [31]. To mitigate WDE, advanced coatings like high-velocity oxygen fuel (HVOF) coatings with hard carbide particles and laser surface treatments that enhance surface hardness are commonly employed [32]. Additionally, blade geometry is vital; optimizing design features such as drainage grooves can help reduce erosion effects [3,33]. Given the critical role of WDE in turbine blade degradation, it is equally important to consider SPE, which also poses significant risks to blade integrity and performance. Understanding the interplay between WDE and SPE provides a comprehensive view of the erosion mechanisms affecting turbine blades, setting the stage for a deeper exploration of SPE in the following section.

3 SPE in steam turbine blades

SPE presents a significant challenge to the structural integrity and operational efficiency of HP steam turbine blades. Notably, the control valve stems, first-stage stationary blade, and moving blade of the HP turbine, as well as the first-stage stationary blade, moving blade of the intermediate or reheat turbine, and the fin region of these stages, are particularly susceptible to SPE [3]. During operation, steam flowing through the turbines' HP section commonly carries solid particles such as dust, sand, or other impurities [34]. Upon collision with the blade surface, these particles generate high-speed erosive impacts. The resulting high velocity and energy lead to material removal or wearing away from the blade surface, a process known as erosion [6,35]. Figure 6 displays a schematic diagram illustrating erosion wear caused by the impact of solid particles.

3.1 Understanding SPE mechanisms

To effectively address SPE, it is crucial to grasp the underlying mechanisms and contributing factors. Parameters like type of erosive particle, particle size, velocity, impact angle, and material properties exert notable influence on the erosion process [36–41]. The investigation findings provide a deeper understanding of the complex dynamics of SPE and offer significant knowledge about how materials function under erosive situations. A study conducted by Laguna-Camacho *et al.* [37] examined the erosion characteristics of AISI 304, 316, and 420 stainless steels, revealing major differences in their erosion tendencies. AISI 420 had excellent resistance to erosion and exhibited ductile behavior regardless of the impact angle. In contrast, AISI 304 and 316 showed higher rates of erosion and suffered considerable wear damage, including detachment of large fragments and brittle fractures. The study also noted that the diameters of wear scars rose when the impact angles were lower (30 and 45°) but decreased when the angles were higher (60 and 90°), with different forms being detected. In addition, the surface roughness experienced a substantial increase following erosion testing, especially when subjected to normal impact angles of 90°. The study by Shitole *et al.* [36] examined copper erosion using quartz, silicon carbide (SiC), and alumina particles, focusing on the impact of particle characteristics and impact angles. The highest erosion wear was observed at shallow impact angles of about 30° for quartz and SiC and approximately 22.5° for alumina (Figure 7). Increased particle angularity led to deeper craters and greater mass loss. Dense, angular particles showed significantly higher erosion rates, emphasizing the relationship between particle form and erosion rate. The results from both researchers highlight the significance of comprehending the interaction among material parameters, particle characteristics, and impact angles in forecasting and reducing SPE in engineering applications.

Additionally, the design of turbine blades and the implementation of protective coatings have a substantial

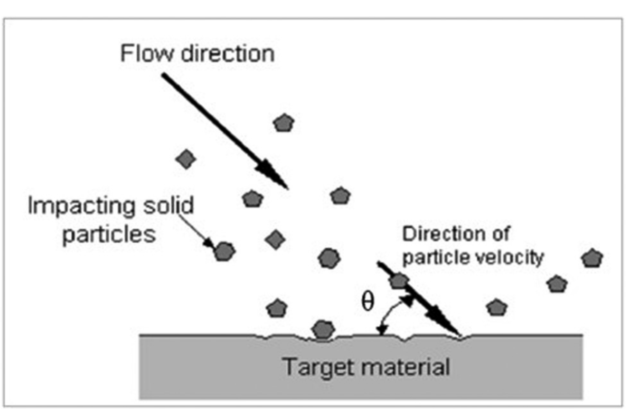

Figure 6: Erosion wear due to SPE. Reproduced from the study of Shitole *et al.* [36].

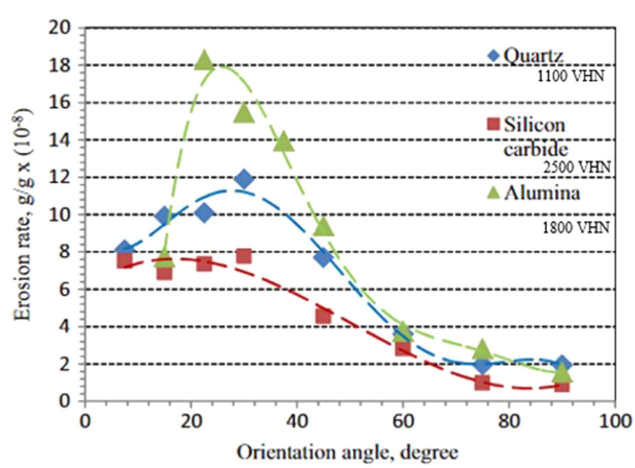

Figure 7: Comparative erosion rates of copper utilizing quartz, SiC, and alumina (d = 362.5 μm, v = 4 m·s^{-1}, c_w = 10%). Source: by Shitole *et al.* [36].

influence on their ability to withstand erosion [42]. A study conducted by Chen *et al.* [43] discovered significant SPE damage on an IP stage 1 turbine after 6 years. The damage was mostly observed on the fixed blade trailing edge and moving blade leading edge. The analysis uncovered that particles known as "bounce back" were responsible for erosion, specifically on the trailing edge of the fixed blade, due to the centrifugal force propelling them outward. Expanding the axial distance between the fixed and moving blade decreased the extent of this damage. Field inspections conducted after a period of 4 years confirmed these findings (Figure 8). The inspections showed that erosion was reduced at the trailing edge of the fixed blade, but damage on the ledge of the moving blade remained. These findings have contributed to a better understanding of the phenomenon known as SPE and have provided valuable insights for designing turbines that can perform better and last longer.

3.2 Materials and design considerations

The composition and hardness of turbine blade materials are crucial factors in determining their resistance to erosion. Materials that possess higher levels of hardness and toughness exhibit enhanced resistance to erosive impacts [12,15,44]. The study, which is conducted by Hawas *et al.* [45], examines several materials and surface treatments to enhance the erosion resistance of turbine blades. Steel, especially when subjected to carburizing treatment, is the optimal choice since it exhibits increased hardness and resistance to erosion. Copper and aluminum are not recommended because they have lower surface qualities. On the other hand, steel with thermal surface treatment shows greater wear resistance, hardness, and toughness. Mukherjee *et al.* [12] propose that Inconel 718 alloy could replace stainless steel in turbine blades, especially for longer ones operating at high temperatures. This alloy maintains mechanical properties under extreme conditions, reducing failures and enhancing turbine efficiency, including resistance to erosion.

Moreover, the design aspects such as blade shape, surface roughness, and aerodynamic characteristics profoundly affect particle impingement and rebound, thereby influencing erosion extent. Leveraging advanced computational modeling allowed for the optimization of blade designs, resulting in improved erosion resistance [1]. Kumaraswamy and Siva Naga Raju's study [13] proposed modifications for HP steam turbine blades that prioritize efficiency through design, manufacturing, and maintenance, ensuring safe operation. These steps are crucial for reducing SPE, prolonging turbine lifespan, and optimizing performance. Leyzerovich [46] investigated SPE resistance in 30 L structural steel, examining nitriding and boriding surface modifications. Boriding degrades erosion resistance at 30 and 90° flow angles due to surface embrittlement, while nitriding enhances resistance by 10–20% at 30° without worsening it at 90°. The study emphasizes the influence of steel composition on erosion resistance, crucial for selecting suitable surface modification techniques to enhance equipment reliability and longevity.

SPE presents a substantial threat to both the structural integrity and operational efficiency of HP steam turbine blades. To effectively address this challenge, it is imperative to thoroughly understand the intricate dynamics of SPE, encompassing factors such as particle characteristics, impact angles, and material properties. In the subsequent sections, will delve into these contributing factors in detail to elucidate their roles in SPE.

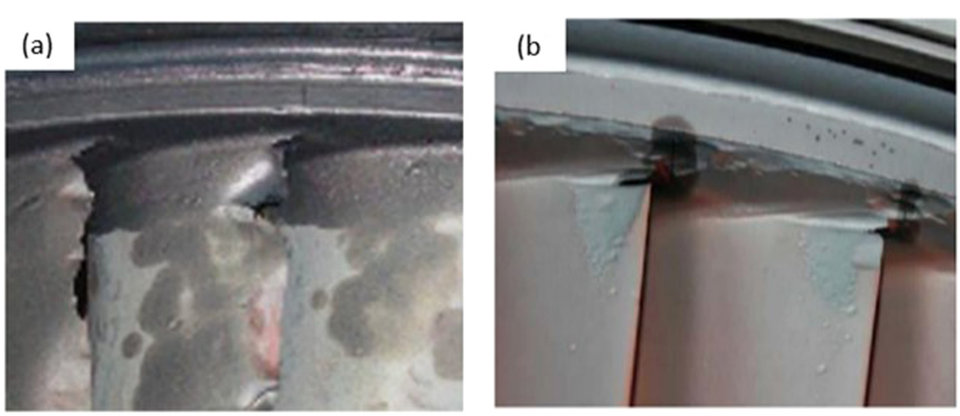

Figure 8: Compares SPE in steam turbine blades before and after modification using the particle trajectory method. (a) Original IP stage 1 SPE damage (6 years) and (b) modified IP stage 1 SPE damage (4 years). Source: from Chen *et al.* [43].

4 Solid particle erosion contributing factors

The effects of SPE on steam turbine blade operation have been extensively studied due to its complex nature, involving multiple processes and parameters requiring thorough analysis. Various factors, including particle velocity, size, shape, concentration, and target material properties, significantly influence the rate of material removal and the mechanisms underlying SPE (Figure 9). Table 1 provides a summary of parameters impacting blade life efficiency affected by SPE. Understanding the interaction of these factors is crucial for developing effective strategies to mitigate SPE and extend turbine blade lifespan. It also has been observed that there is a limited amount of experimental research on steam turbine blade performance compared to simulation studies. The majority of publications regarding steam turbine blade analysis are based on simulation results, often utilizing software such as Abaqus or Ansys.

4.1 Effect of velocity

The most concerning parameter impacting erosion rates appears to be the velocity of the erosive particles. Higher particle velocities generally result in increased erosion rates, as observed in studies [39,40]. To achieve a low erosion rate, it is advisable to minimize particle velocities during turbine operation. Among the studies analyzed, Di *et al.* [48] investigated the erosion of turbine blades made of 1Cr12W1MoV steel by tiny, high-speed particles. The researchers analyzed how particle shape, size, and speed influence blade damage rates, aiming to enhance blade durability. It found that the erosion rate decreased when the impact velocity of the particles was lower. Specifically, at lower impact speeds, the erosion rate was mitigated, indicating that reducing particle velocity can lead to lower erosion rates. This finding underscores the critical role of particle velocity in SPE and suggests that controlling particle velocities could be an effective strategy for minimizing erosion rates in turbine blades.

4.2 Impingement angle

In the quest to minimize erosion rates, optimal parameter values often hinge on the unique conditions and materials involved. Research has indicated that lower impact angles, specifically 30°, are associated with increased erosion rates in comparison to angles that are greater [8,36,37,48]. Therefore, it is highly recommended to optimize the angle of impact towards higher values to reduce erosion. Zhang

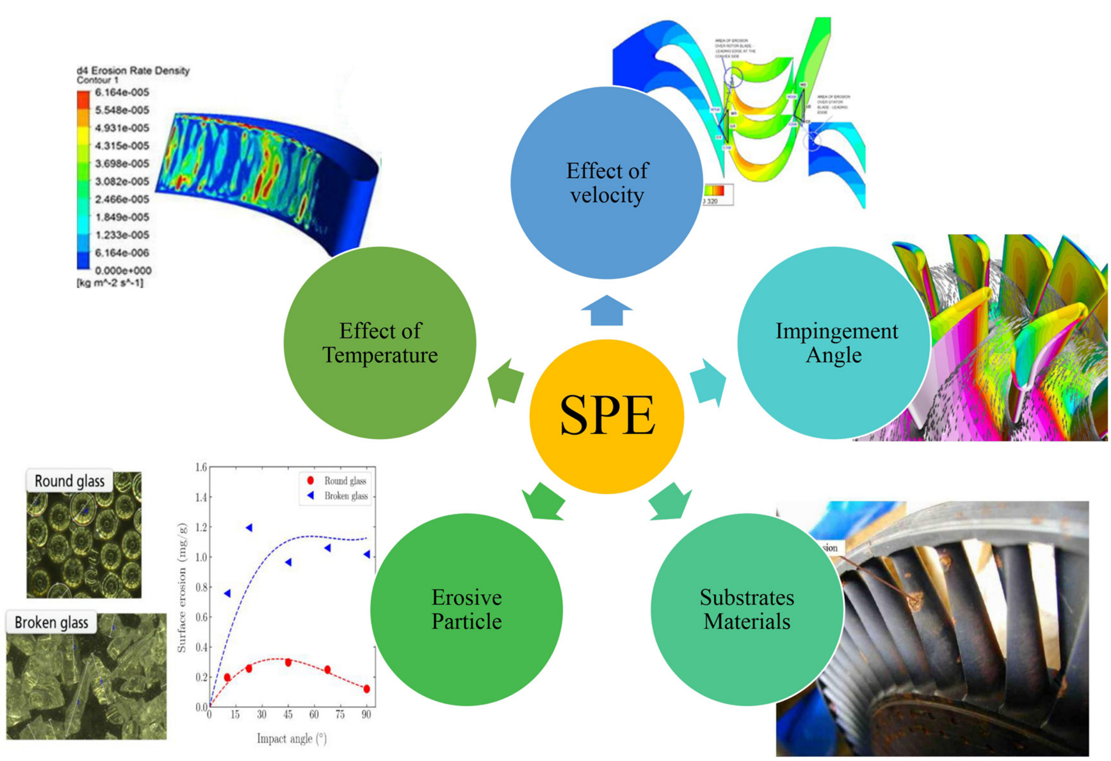

Figure 9: Key contributing factors to SPE on steam turbine blade [47].

Table 1: Properties influencing SPE in steam turbine blades

		(a) Effect of velocity	(b) ImpiNgEment angle	(c) Substrate material		(d) Erosive particle			(e) Effect of temp.			
Ref.	Aim of study	Impact speed ($m \cdot s^{-1}$)	Angle	Substrate material	Substrate hardness (HV)	Erosive particle	Particle size (μm)	Particle flow rate	Temp.	Duration	Erosive rate	Erosive result
[36]	The study examines how different solid particles affect erosion on ductile materials using a slurry pot tester. Focusing on copper, it considers particle properties like shape and density at various angles, particularly when exposed to quartz, SiC, and alumina particles	5.50	30–90°	Copper	120	Quartz, SiC, and alumina	362.5	—	—	15–40 min	8–18 $g \cdot g^{-1}$ × (10^{-8})	Maximum erosion occurred at shallow angles (30° for quartz and SiC, 22.5° for alumina). Particle angularity affected erosion rates, with higher angularity causing deeper craters and more mass loss. Dense and angular particles showed notably higher erosion rates, emphasizing the link between particle shape and erosion.
[37]	The study aimed to evaluate the SPE performance of AISI 304, 316, and 420 stainless steels. It assessed erosion behavior under varying impact angles and abrasive flow rates, identifying wear mechanisms and damage characteristics. Comparison of erosion resistance aimed to determine the most resistant material. Additionally, roughness changes on surfaces were analyzed using atomic force microscopy	24 ± 2	30, 45, 60, and 90°	AISI 304, 316, and 420	AISI 304: 160, AISI 316: 150, and AISI 420: 200–240	SiC	420–450	150 ± 0.5 $g \cdot min^{-1}$	35 and 40°C	10 min	3.75 × 10^{-04} $g \cdot g^{-1}$–6.74 × 10^{-05} $g \cdot g^{-1}$	AISI 304 and 316 had higher erosion rates at 60°, while AISI 420 exhibited the highest erosion damage at 30°. AISI 420 displayed superior performance with ductile behavior, while AISI 316 and AISI 304 showed brittle behavior, reaching maximum erosion rates at 60°. Wear scars increased in size at lower impact angles (30 and 45°) and decreased at 60 and 90°, with elliptical shapes at 30 and 45°, and roughly circular shapes at 60 and 90°.
[49]	The study investigates salt particle behavior on steam turbine blades using computer models. Understanding particle formation, growth, aggregation, and dispersion aids in optimizing turbine efficiency and longevity by mitigating salt-induced damage	—	—	—	—	Salt (sodium chloride)	—	—	Superheated	Time step 8.9 × 10^{-7} s	—	The erosive rate is higher where the steam is more turbulent, which means where it's moving in a more chaotic way, because this causes more collisions between the particles and the blades
[39]	The study aims to understand how small, hard particles cause damage to compressor blades, a major cause of failure. It employs a specialized computer model to analyze how factors like impact angle, particle speed, and size affect damage at varying temperatures. This aids in designing more durable compressor blades by predicting potential damage locations and patterns over time	75	15–75°	Titanium alloy Ti-6Al-4V	—	Alumina	80–120	—	298, 473, and 623 K.	4 h	0.1–0.3 $mm^3 \cdot g^{-1}$	Erosive rate varies with impact angle, with the lowest rate at 15° and the highest around 42° at 298 K. Additionally, higher particle velocity correlates with faster erosion, with rates of 2.5 at 298 K, 2.8571 at 473 K, and 2.3333 at 623 K. Particle size also influences erosion, particularly evident at higher temperatures like 623 K.
[40]	The study identified AA7075-T651 aluminum as the most resilient to damage from small, hard particles on airplane wing fronts. Wear increases with faster particle speeds and peaks at a 30° angle. Computer simulations revealed a slight increase in wear when the wing part is turned 5°	70, 114, 165, 130, 192, and 250	30 and 60°	Aluminum alloys: AA2024-T351, AA6061-T651, and AA7075-T651	AA2024-T351: 120, AA6061-T651: 95, AA7075-T651: 145	SiC	106–150	5.8 $g \cdot cm^{-2}$	—	—	112.23–2940.25 $mm^3 \cdot kg^{-1}$	A study found that AA7075-T651 aluminum was the most durable and showed the least wear when struck by small, hard particles on an airplane wing's leading edge. In contrast, AA6061-T651 aluminum experienced the most wear. The wear increased with particle speed and was most pronounced at a 30° angle. SiC particles were used in the tests

(*Continued*)

Table 1: *Continued*

		(a) Effect of velocity	(b) ImpiNgEment angle	(c) Substrate material		(d) Erosive particle			(e) Effect of temp.			
Ref.	Aim of study	Impact speed ($m \cdot s^{-1}$)	Angle	Substrate material	Substrate hardness (HV)	Erosive particle	Particle size (μm)	Particle flow rate	Temp.	Duration	Erosive rate	Erosive result
[8]	• The study aims to comprehend the erosion caused by solid particles on critical components of a large steam engine, impacting efficiency and maintenance costs. Using computer simulations, researchers investigate the influence of particle size and engine part speed on wear, particularly in the control section. They seek to identify the most affected engine parts and understand the movement and impact of solid particles on these components	322	0–90°	—	—	—	7.5, 15, 25, 40 and 75	0.00024–0.06751 $kg \cdot s^{-1}$	—	—	3.930×10^{-006} $kg \cdot (m^{-2} s^{-1})$–6.755×10^{-004} $kg \cdot (m^{-2} s^{-1})$	• The study found that smaller particles at smaller angles cause less damage, while larger particles at larger angles cause more erosion. A shaded area in the figure indicates the optimal erosion angle, where larger particles (75 μm) cause significant damage. Larger particles also lead to greater weight loss, with the back part of the blades experiencing the most erosion. Small particles (7.5 μm) have a low erosive rate of approximately 3.930×10^{-006} $kg \cdot (m^{-2} s^{-1})$, causing minimal damage, while large particles (75 μm) have a much higher erosive rate of around 6.755×10^{-004} $kg \cdot (m^{-2} s^{-1})$, resulting in rapid wear of turbine parts.
[48]	The study investigates the erosion of turbine blades made of 1Cr12W1MoV steel by tiny, high-speed particles. Researchers analyze how particle shape, size, and speed influence blade damage rates, aiming to enhance blade durability and performance in dusty environments	150, 210, and 350	24–30 and 45–60°	Martensitic steel 1Cr12W1MoV	—	Iron oxide	10–80	—	566°C	—	0.1–2.4 $cm^3\ kg^{-1}$	• Erosive rate rises with higher impact speeds. Flaky particles peak at 24°-30° angles, while spherical particles peak at 45°-60°. At 210 $m \cdot s^{-1}$ impact speed, flaky particles reach maximum erosion within the 24°-30° range. At 350 $m \cdot s^{-1}$, spherical particles exhibit slightly higher erosion rates than flaky ones. Erosive rates vary based on particle shape, size, impact velocity, and angle
[38]	The study investigated the impact of axial clearance on two aspects of a steam turbine: SPE rate and turbine efficiency. Researchers examined how altering the clearance affects blade wear and turbine performance	—	—	—	—	—	7.5, 15, 25, 40, and 75	0.00024–0.06751 $kg \cdot s^{-1}$	593°C	—	0.0002043–0.001742 $kg \cdot m^{-2} s^{-1}$	• Blade erosion varies with the space between blades and other parts. A larger space reduces wear, lowering erosion rates by approximately 59.2%. The highest wear rate was 0.001742 $kg \cdot m^{-2} s^{-1}$ in a detailed simulation, while the lowest was 0.0002043 $kg \cdot m^{-2} s^{-1}$ in a simpler simulation.
[41]	The study aimed to analyze erosion on SS-316 steel caused by water-rock slurry impact, seeking optimal conditions to minimize damage in applications like power plants and engines	14.7 and 30.6	30–90°	Stainless steels (SS 316)	152	Sand (SiO_2)	<300	—	25°C	10 min	1.45–1.97 $mg \cdot min^{-1}$	• At a 90° angle and 14.7 $m \cdot s^{-1}$ velocity, erosion rates were 1.45 $mg \cdot min^{-1}$ at 0.5% slurry concentration and slightly higher at 2.28%. At a 30° angle and 30.6 $m \cdot s^{-1}$ velocity, erosion rate increased to 1.97 $mg \cdot min^{-1}$ at 0.5% slurry concentration

et al. [8] conducted a significant study that extensively examined the influence of impingement angle on the rates of SPE, specifically on important components in big steam engines. By utilizing advanced computer simulations, their study revealed a complex correlation: smaller particles at shallower angles cause less harm, resulting in lower rates of erosion. In contrast, when larger particles collide with surfaces at steeper angles, they cause more substantial erosion, resulting in increased erosion rates. The main point of their research highlights the crucial significance of impingement angle in determining erosion rates and emphasizes the necessity of considering angle effects when assessing SPE in turbine components. For example, their research reveals that smaller particles at shallower angles (*e.g.*, 7.5 µm at 0°) cause less damage, resulting in low erosion rates. On the other hand, larger particles landing at steeper angles (*e.g.*, 75 µm at 90°) cause significant erosion, leading to higher erosion rates. These revelations highlight how important it is to carefully consider angles when estimating erosion rates.

4.3 Substrates material

Materials with higher hardness and resistance, such as AISI 420 stainless steel, tend to exhibit lower erosion rates compared to materials like copper [36,37]. Selecting substrates with superior hardness and resistance properties can contribute to lower erosion rates. As the study by Laguna-Camacho *et al.* [37], the study evaluated the SPE performance of AISI 304, 316, and 420 stainless steels under varying impact angles and abrasive flow rates, employing SiC as the abrasive material. AISI 420 demonstrated superior erosion resistance with minimal wear damage and ductile behavior across all impact angles, contrasting AISI 304 and 316, which exhibited higher erosion rates and significant wear damage, including brittle fracture. Notably, AISI 420 higher hardness and resistance resulted in lower erosive rates compared to AISI 304 and 316, highlighting the correlation between material hardness and erosion resistance. Furthermore, surface roughness increased notably post-erosion tests, particularly at normal impact angles (90°). The other study by Budur *et al.* [40] investigated SPE, focusing on aluminum alloys AA2024-T351, AA6061-T651, and AA7075-T651, using SiC particles. AA7075-T651 emerged as the most resilient to SPE, exhibiting minimal wear compared to AA2024-T351 and AA6061-T651. The erosion intensity increased with particle speed, peaking at a 30° impact angle. The study emphasized the correlation between material hardness and erosion resistance, highlighting AA7075-T651's superior performance in mitigating SPE damage.

4.4 Erosive particles

Understanding the specific characteristics of erosive particles like quartz, SiC, alumina, salt, and iron oxide is crucial

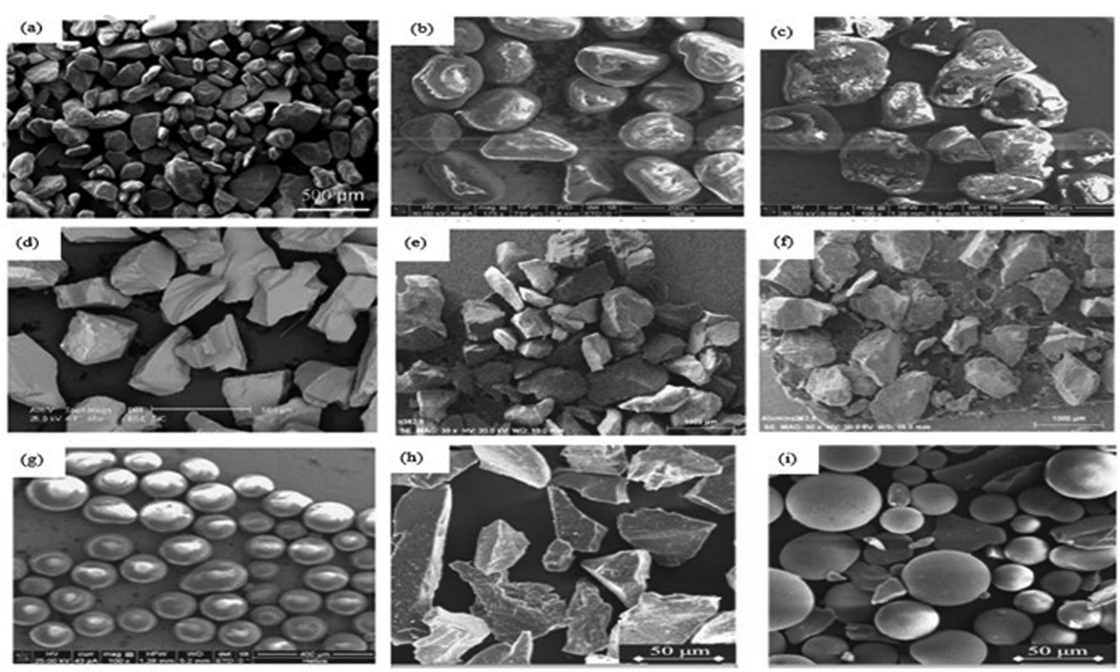

Figure 10: Particle materials and shapes of SPE used in studies. (a) 500 µm sand [50], (b) 150 µm semirounded sand [36,51], (c) 300 µm sharp sand [36], (d) SiC [37], (e) quartz [36], (f) alumina [36], (g) 150 µm glass beads [51], (h) 50 µm Al_2O_3 [52], and (i) 50 µm SiO_2 [52]. Reproduced from [36,37,50–52].

for minimizing erosion rates, as different particles exhibit varying erosion rates [36,37,48,49]. Factors such as material composition, size, and shape significantly contribute to erosion rates. For instance, alumina particles generally result in higher erosion rates compared to SiC and quartz [36,37]. Figure 10 illustrates a range of particle materials, shapes, and sizes used in investigating SPE. The study by Shitole *et al.* [36] delves into the impact of different solid particles on the erosion of ductile materials, particularly focusing on copper. Utilizing a slurry pot tester, it investigates erosion caused by quartz, SiC, and alumina particles across various impact angles (30–90°), revealing that maximum erosion occurs at shallow angles, notably 30° for quartz and SiC, and 22.5° for alumina. Moreover, the study underscores the influence of particle angularity on erosion rates, with denser and more angular particles exhibiting higher erosion rates, thereby emphasizing the critical role of particle shape in erosion behavior.

4.5 Effect of temperature

Recognizing the impact of temperature on the rates of SPE also is crucial for evaluating and reducing damage to compressor blades, which is a significant contributor to turbine component failure. Mohammadi and Khoddami [39] conducted a study that extensively investigated the influence of temperature on SPE rates using a specialized computer model. The research examines the relationship between temperature and erosion rates by investigating variables such as impact angle, particle speed, and size within a temperature range of 298–623 K. Their findings reveal a significant correlation between higher temperatures and accelerated erosion rates, emphasizing the crucial role of temperature in SPE dynamics. This highlights the importance of thoroughly addressing temperature effects for predicting and managing damage caused by SPE in turbine components.

To achieve low SPE rates in turbine components, optimizing key parameters is essential. Lower particle velocities, higher impact angles, materials with superior hardness and resistance, suitable types of erosive particles, and lower temperatures within the suggested range contribute to minimizing erosion rates. Studies indicate that reducing particle velocities mitigates erosion, while higher impact angles and materials like AISI 420 stainless steel exhibit lower erosion rates. Additionally, SiC particles result in lower erosion rates compared to alumina particles. Lower temperatures, typically within the range of 298–623 K, correlate with lower erosion rates, while higher temperatures accelerate erosion. Understanding and optimizing these parameters are crucial for effectively mitigating SPE and preserving turbine component integrity and performance. In conclusion, optimizing parameters such as particle velocity, impact angle, substrate material, temperature, and type of erosive particle is crucial for minimizing erosion rates in turbine blades. Understanding the interactions between these parameters can help devise effective strategies to mitigate SPE and enhance turbine durability and performance.

5 Coating technology for SPE mitigation

SPE poses a significant challenge across various industries, from aerospace to energy and manufacturing. To effectively prevent this erosion, it is necessary to use resistant coatings and materials [53–57]. These coatings must withstand high-speed impacts and minimize material loss, making advanced coating technologies essential.

Among these technologies, nanocomposite coatings, particularly those based on graphene, show potential for improving erosion resistance [58–62]. Furthermore, current research is exploring self-healing coatings and enhanced ceramic materials, which have the potential to make significant advancements in reducing erosive particle damage [63,64]. By investing in the research and implementation of these advanced coating technologies, it is possible to greatly extend the lifespan and improve the performance of essential components when faced with SPE difficulties.

Recent studies have specifically focused on creating advanced coatings that possess enhanced adhesion, hardness, and erosion resistance. These coatings aim to enhance the durability of turbine blades when exposed to challenging operating conditions. A comprehensive compilation of studies regarding coating treatments on SPE, as summarized in Table 2, provides valuable insights into key parameters such as coating process, material, substrate, thickness, erosive particle characteristics, test conditions, and observed outcomes. This compilation is a useful resource for researchers and practitioners who are working to improve coatings for the purpose of reducing erosive wear.

5.1 Coating composition and material used

The protective coatings investigated in the reviewed studies encompass a diverse array of materials and application methods. Materials such as yttria-stabilized zirconia (YPSZ),

Table 2: Comparative analysis of coating effects on erosion behavior

Ref.	Application (component)	Coating process	Coating material	Substrate	Coating thickness	Erosive particle	Particle hardness	Particle flow rate	Particle size	Temp. erosion test	Impact speed	Angle	Erosive rate	Observation
[72]	Gas turbines (blade and vanes)	TBS and APS	YPSZ and YAG	Nickel superalloy (Rene80)	250–750 μm	Alumina	—	1.7 g·min^{-1}	400 mesh fine: D_{10} = 10 μm, D_{50} = 16.7 μm, D_{90} = 27.8 μm 150 mesh coarse: D_{10} = 70 μm, D_{50} = 126 μm, D_{90} = 198 μm	1,000°C	60 ± 3 and 104 ± 5 m·s^{-1}	90°	0.06–4.86 mm^3·g^{-1}	• Higher erosion rates at 90° compared to 30° impingement angles. Additionally, porous TBCs exhibited higher erosion rates at elevated temperatures • A new bilayer coating with a unique microstructure showed promising erosion resistance, especially against fine particles. Double-layer TBCs exhibited varying erosion rates due to differences in solid particle resistance between layers
[65]	Steam turbine (turbines and boiler tubes)	APS and HVOF	WC-Cr_3C_2-Ni	Stainless steel 316 L	APS 345 mm, and HVOF 387 mm	Alumina	27 GPa	—	50 μm	500 and 650°C	—	30 and 90°	0.22 ± 0.06–1.60 ± 0.09 × 10^3 (g·g^{-1})	• The erosion resistance of WC-Cr_3C_2-Ni coatings, applied *via* APS and HVOF processes, was two to four times higher than that of uncoated specimens at elevated temperatures, with erosion rates for coated specimens being directly proportional to the impact angle • Factors such as temperature, impact angle, material hardness, porosity, splat adhesion, decarburization, and inter-splat sintering influenced the erosion behavior, with hard carbides in the coatings contributing to their improved resistance compared to uncoated specimens
[93]	Gas turbine (turbine blades and vanes)	TBS and APS	CoNiCrAlY and YPSZ	Inconel 718	—	Alumina	—	13 g·s^{-1}	76.25 μm	25°C	27 m·s^{-1}	30° 60 and 90°	0.28–0.60 × 1,000 (mg·g^{-1})	• The maximum erosion rates were observed at a 60° impingement angle, indicating a semi-ductile/semi-brittle erosion behavior • The surface roughness values and topographies of the eroded specimens varied depending on the impingement angle, with deeper and wider erosion craters formed at a 60° impact angle
[94]	—	FCVA technique	TiN/Ti (MLG-TiN/Ti)	Ti6Al4V alloy	TiN/Ti (MLG-TiN/Ti) 10.35 mm to 10.81 mm and MLG-4 12.09 μm	Sand SiO_2	—	2 g·min^{-1}	100–300 μm	—	130 m·s^{-1}	45°	0.085–0.3 m-g·g^{-1}	• The MLG-4 coating, with a thickness of 12.09 μm and composed of TiN layers, Ti layers, and gradient layers, exhibited the lowest erosion rate among both MLG-TiN/Ti and ML-TiN/Ti coatings • MLG-TiN/Ti coatings demonstrated superior resistance to crack and erosion damage compared to ML-TiN/Ti coatings, with the latter showing a slight initial decrease in erosion rates before increasing with more layers, peaking at 0.085 mg·g^{-1} for the four-layer variant
[77]	Steam turbine (blades and nozzles)	Arc ion plating (AIP)	TiN and TiAlN	12Cr steel	>20 μm	Alumina	20 GPa	—	300 μm	25, 600 and 700°C	50 m·s^{-1}	30 and 90°	—	• The TiAlN coating exhibited high-temperature stability, resistance to SPE, and maintained substrate material's high-temperature fatigue and creep properties, making it suitable for steam turbine applications

(*Continued*)

Table 2: *Continued*

Ref.	Application (component)	Coating process	Coating material	Substrate	Coating thickness	Erosive particle	Particle hardness	Particle flow rate	Particle size	Temp. erosion test	Impact speed	Angle	Erosive rate	Observation
														• It demonstrated excellent performance on steam turbine blades, with no delamination or chipping at the blade trailing edge, and retained high hardness at elevated temperatures, ensuring erosion resistance during operation
[78]	Steam turbine (blades)	Cathodic arc ion plating	Titanium Aluminum Nitride (TiAlN)	WC-Co WC -cobalt mix, and 17-4 PH stainless steel	5–10 mm	Alumina	20 GPa	—	40 μm	25°C	100 m·s^{-1}	90°	0.036–2.7 μm·min^{-1}	• The study found that TiAlN coatings with an aluminum ratio of up to 0.58 exhibited optimal erosion resistance. Coatings with higher aluminum ratios experienced accelerated wear due to structural changes. Coatings with balanced hardness and Young's modulus showed slower wear
[8]	First-stage steam turbine (blade and rotor)	—	Ceramic	Metal	—	—	—	—	7.5, 15, 25, 40, and 75 μm	—	277–322 m·s^{-1}	20–35°	3.930 × 10^{-006} kg·(m^{-2} s^{-1})–1.332 × 10^{-003} kg·(m^{-2} s^{-1})	• The nozzle experiences minimal wear from 7.5 mm particles at 3.930 × 10^{-006} kg·(m^{-2} s^{-1}), while the rotor blade faces significantly higher wear from 75 mm particles at 1.332 × 10^{-003} kg·(m^{-2} s^{-1}) • As particles increase in size, their movement shifts, causing more damage to steam turbine parts. Wear is most pronounced in the middle to back of the nozzle and the front edge and middle to back of the rotor blade, exacerbated by higher turbine speeds. Minimizing particle impact angles between 20 and 35° can prolong turbine lifespan and enhance performance
[95]	Jet engine (blade)	Environmental barrier coating EBC (PS-PVD)	Ytterbium disilicate (Yb2Si2O7)	SiC	225–275 μm	Alumina (Al_2O_3)	—	—	27, 60 and 150 μm	1,200°C	135 m·s^{-1}	30, 60, and 90°	10.72–21.75 m-g·g^{-1}	• When particles hit at 90°, more coating material was lost compared to angles like 30°. The coatings' initial surface roughness affected its rate of wear • The study examined the wear of a specialized coating under hot, engine-like conditions, finding its wear pattern similar to other engine coatings. Particle speed, angle of impact, and coating roughness were identified as factors influencing wear rate. Lower angles resulted in grooves or scars on the coating, contributing to its wear
[85]	Airplane (compressor blades, vanes, and impellor blisk wheels)	Cathodic arc deposition	CrAlTiN and AlTiN	17-4PH stainless steel	16–21 μm	Alumina (Al_2O_3)	—	1 g·min^{-1}	50 μm	25°C	84 m·s^{-1}	30 and 90°	76.4 mg·g^{-1} and 164.1 mg·g^{-1}	• CrAlTiN coatings significantly outperformed basic CrN coatings in erosion resistance, with one type showing only 25 and 16% of CrN's erosion rate at 30° and 90°, respectively; the multilayered CrAlTiN-AlTiN coating with 15 layers each exhibited the lowest erosion rates

(*Continued*)

Table 2: *Continued*

Ref.	Application (component)	Coating process	Coating material	Substrate	Coating thickness	Erosive particle	Particle hardness	Particle flow rate	Particle size	Temp. erosion test	Impact speed	Angle	Erosive rate	Observation
														• Special thin-layered coatings were more effective than conventional CrN coatings in protecting engine parts from wear, with increased layer numbers enhancing strength and optimal protection achieved through precise layer composition
[34]	Turbomachinery (fans and compressor blades)	Plasma-enhanced magnetron sputtering	mix of chromium (Cr), silicon (Si), carbon (C), and nitrogen (N)	stainless steel 17-4 PH	20 µm	Alumina (Al_2O_3)	—	1.5 g·min^{-1}	50 µm	—	60 m·s^{-1}	30 and 90°	0.01–0.07 mg·g^{-1}	• Coatings with higher hardness and resistance to bending had lower erosion rates at shallow angles (30°), while those less brittle and more resistant to cracking performed better at steep angles (90°) • The CrSiCN(2) coating, with lower brittleness, showed the lowest erosion rate at angles above 60°, indicating erosion rates vary based on impact angle and properties like hardness, brittleness, and cracking resistance
[96]	Steam turbine (blades)	HVOF and boride coating (solid power boronization)	Cr_3C_2, FeB, and Fe2B phases	Metal	—	Iron oxide, Fe_3O_4 and Fe_2O_3	5.5 Mohs scale	10 Nm^3·min^{-1}	150 mesh size	811 and 839 K	210 or 350 m·s^{-1}	12, 24, 30, 36, 45, 60, 75, and 90°	0.01–2.70 mg·g^{-1}	• Boride coatings exhibit significantly lower erosion rates compared to HVOF Cr_3C_2 coatings, ranging from 30 to 50% under identical test conditions. Even at higher particle velocities (350 m·s^{-1}), boride coatings still demonstrate superior resistance, with erosion rates approximately 70% of those observed for HVOF Cr_3C_2 coatings
[86]	Gas turbine (Blade)	HVOF	Stellite-6, Alumina-CoCrAlTaY and Cr_3C_2-NiCrNiCrAlY	Titanium alloy (Ti-6Al-4V), Cobalt-based superalloy	—	Silica sand	880Hv	5 g·min^{-1}	125–180 µm	25°C	40 m·s^{-1}	30, 60, and 90°	(0.1–20 cm^2·g^{-1}) × 10^{-5}	• Stellite-6 showed superior resistance to wear at a 30° particle impact angle compared to other coatings tested, suggesting its effectiveness in mitigating damage • Erosion rates varied based on particle size and impact speed, with larger and faster particles causing more damage. Additionally, the impact angle influenced erosion rates, with coatings' composition affecting resistance differently at low and high angles
[67]	Various industries (impeller blade)	APS	NiCr (Nickel Chromium) and Cr_3C_2	FV520B martensitic stainless steel,	15–45 µm and 45–75 µm	AluminaA-l_2O_3	2,361 Hv	4 g·min^{-1}	7, 10, and 14 µm	25°C	240 m·s^{-1}	12, 45, 60, and 90°	0.3–1.6 mg·g^{-1}	• Coating erosion rates follow a pattern of initial increase and subsequent decrease with solid particle size increase, with maximum erosion rates at specific particle sizes relative to impact angles, indicating a variable range of erosion rates dependent on both factors • NiCr-Cr_3C_2 coatings show varying resistance levels to particle-induced damage at different NiCr contents and impact angles, with increased NiCr content potentially compromising hardness but enhancing impact absorption, highlighting the need for optimized coating compositions based on impact angle and particle speed

(*Continued*)

Table 2: *Continued*

Ref.	Application (component)	Coating process	Coating material	Substrate	Coating thickness	Erosive particle	Particle hardness	Particle flow rate	Particle size	Temp. erosion test	Impact speed	Angle	Erosive rate	Observation
[68]	Industrial applications.	HVOF and HVAF	Cr_3C_2-25NiCr Cr_3C_2-50NiCrMoNb Cr_3C_2-37WC-18NiCoCr WC-10Co4Cr	low carbon steel	—	Quartz sand (SiO_2)	—	25 g·min^{-1}	0.1–0.6 mm	ambient conditions	80 m·s^{-1}	30 and 90°	0.3–2.3 mm^3·kg^{-1}	• Coatings with higher carbide content and microhardness exhibited lower erosion rates, particularly evident at a 90° impact angle, emphasizing resistance to particle penetration • Increasing carbide content reduced the difference in erosion rates between 30 and 90°, highlighting the significant impact of particle angle on material loss • HVAF demonstrated superior erosion resistance compared to HVOF indicating potential for increased durability against high-speed particle impacts
[81]	Gas turbines and other critical power generation components	APS	Cr_3C_2 and nickel-chromium (NiCr) composite	stainless steel SS 304-L and SS-316-L	150–250 µm	Alumina	15 GPa	30 g·min^{-1}	50 µm	23°C	—	45°	8.27–9.59 mm^3·min^{-1}	• Enhanced coating S5 showed significantly lower erosion rates (8.27 mm^3·min^{-1}) compared to the base coating S1 (10.06 mm^3·min^{-1}), indicating increased erosion resistance • Incorporating hard particles like Cr_2O_3 and B_4C into Cr_3C_2-NiCr coatings improves wear resistance, with coatings containing a 10% weight fraction of Cr_2O_3 demonstrating superior performance, reduced wear rates, and enhanced resistance to abrasion
[69]	Industries steam turbine	HVOF	Mix SiC, WC, and Cr_3C_2 powders	AISI 304 stainless steel	240 µm	Silica sand	—	—	312 µm	25°C	—	—	—	• The erosive rate rises with longer exposure to particles, indicating increased material wear over time. SiC-WC-Cr_3C_2 multilayer coatings exhibit superior wear resistance compared to uncoated samples, effectively protecting the underlying material from erosion • The SiC-WC-Cr_3C_2 multilayer coating significantly enhances AISI 304 stainless steel hardness, increasing its resistance to high-speed particle wear. With longer exposure to erosive particles, both coated and uncoated samples exhibit increased material wear, but coated samples sustain less damage
[73]	Hardmetal coatings to protect components,	HVOF and HVAF	WC with cobalt and chromium and Cr_3C_2 with nickel and chromium	Low carbon steel (S235) and stainless steel (AISI 316 L)	—	Quartz sand	1,100 HV	—	0.1–0.6 mm	—	80 m·s^{-1}	30, 60, and 90°	0.3–1.8 mm^3·kg^{-1}	• HVAF sprayed WC-10Co4Cr coatings exhibited significantly lower cavitation erosion rates (0.4 µm·h^{-1}) compared to HVOF sprayed coatings (1.5–3.7 µm·h^{-1}), highlighting HVAF effectiveness in reducing wear • In slurry erosion tests with fine quartz sand (0.1–0.6 mm), both HVAF and HPHVOF sprayed WC-10Co4Cr coatings showed minimal volume losses, demonstrating high wear

(*Continued*)

Table 2: *Continued*

Ref.	Application (component)	Coating process	Coating material	Substrate	Coating thickness	Erosive particle	Particle hardness	Particle flow rate	Particle size	Temp. erosion test	Impact speed	Angle	Erosive rate	Observation
														resistance, with HVAF coatings maintaining superior performance even with larger quartz particle sizes (2–3 mm)
[97]	Steam turbine blades	HVOF	Hard-metal layer of Cr_3C_2 with nickel chromium	304 stainless steels	300 μm	Alumina	—	150 g·min^{-1}	250 μm	25°C	keep constant	90°	—	• Coating erosion resistance decreases as the stoichiometry factor increases, with optimal erosion resistance observed at stoichiometry factors around 1 or lower, correlating with lower porosity and higher mechanical properties like hardness and toughness • Adjusting oxygen and ethanol mix influences coating structure and performance, with stoichiometry factors below 1 leading to superior mechanical properties and erosion resistance, highlighting the importance of fuel mixture for high-quality coatings
[83]	—	Multiple graphene-based	Graphene-based materials H-146 and IA-700, Carbothane 134 HG	—	25, 75, 50,125 mm	silica sand (SiO_2)	—	0.067 g·s^{-1}	206 μm	—	20 m·s^{-1}	30–90°	0.001 × 10^{+00}–7.00 × 10^{-05} g·g^{-1}	• Different coatings affect material wear rates differently, with H-146 graphene and multiple layers of polyurethane showing improved wear reduction, up to 19 and 38%, respectively • Coating effectiveness is influenced by the angle of attack, erosion duration, and surface smoothness, highlighting the importance of these factors in providing protection against particle impact
[84]	Power generation industry (turbiine blade)	HPCS	Inconel 738	T11 boiler steel	126-9 μm	Alumina (Al_2O_3)	14 GPa	2 g·min^{-1}	50 μm	700°C	30 m·s^{-1}	30 and 90°	0.3–27 × 10^{-4} g·g^{-1}	• The study found that Inconel 738 coated specimens exhibit significantly lower erosion rates compared to uncoated T11 steel at 700°C, offering better protection against high-temperature erosion. Specifically, at 30 and 90° impact angles, the coating shows approximately three- and two-times higher erosion resistance, respectively, than T11 steel • The erosion rate of coated specimens is higher at a 30° impact angle than at a 90° angle, indicating the angle's influence on material wear

yttrium aluminum garnet (YAG), WC-Cr_3C_2-Ni, CoNiCrAlY, titanium aluminum nitride (TiAlN), chromium carbide (Cr_3C_2), boride coatings, and various hard-metal compositions are explored for their erosion and SPE resistance. These coatings are applied onto substrates ranging from nickel superalloys and stainless steel to titanium alloys and low-carbon steel. Coating thickness varies considerably, spanning from 5 to 750 µm, depending on application requirements. Notably, the study by Bhosale *et al.* [65] stands out for its investigation into differences in coating material and thickness and their impact on erosion rates. They examined WC-Cr_3C_2-Ni coatings deposited by atmospheric plasma spray (APS) and HVOF processes on stainless steel substrates. By varying the coating thickness (APS 345 mm and HVOF 387 mm) and utilizing alumina as the erosive particle, they demonstrated significantly lower erosion rates compared to uncoated specimens at elevated temperatures. This study underscores the critical role of coating material and thickness in achieving optimal erosion resistance, offering valuable insights for the development of erosion-resistant coatings.

5.2 Coating parameter effects on erosive rate

The influence of several parameters on the erosive rate is highlighted in Table 2, including particle size, impact angle, coating composition, deposition method, substrate material, and temperature. Studies indicate that erosion rates are affected by factors such as material hardness, microstructure, and resistance to cracking. For instance, coatings with higher carbide content and microhardness tend to exhibit lower erosion rates due to their enhanced resistance to particle impact. Hierarchical coatings, with varying layer thicknesses, offer superior wear resistance and strength compared to single or multi-layered coatings [66]. Li *et al.* [67] found that NiCr-Cr_3C_2 coatings with varying NiCr amounts exhibit different levels of resistance to particle-induced damage at various speeds and angles. Increasing NiCr content decreases coating hardness but increases porosity, potentially improving impact absorption while compromising overall durability. Matikainen *et al.* [68] observed that coatings with higher carbide content and microhardness exhibited lower erosion rates, particularly evident at a 90° impact angle, emphasizing resistance to particle penetration. Rao *et al.* [69] noted that SiC-WC-Cr_3C_2 multilayer coatings significantly enhance the hardness of stainless steel, increasing its resistance to high-speed particle wear.

Erosion testing conditions simulate operational environments with temperature tests conducted at temperatures ranging from 25 to 1,000°C. Impact speeds vary between 27 and 135 $m \cdot s^{-1}$, while impingement angles range from 12 to 90°, affecting the distribution and intensity of particle impact on coated surfaces [70,71]. This comprehensive exploration provides valuable insights into the performance of protective coatings under erosive conditions, contributing to the advancement of erosion-resistant materials for diverse industrial applications. Alumina (Al_2O_3) emerges as the predominant erosive particle, although silica sand (SiO_2) and quartz sand are also utilized. These particles exhibit a wide range of hardness, from 20 to 27 GPa, and are delivered at flow rates ranging from 0.067 to 30 $g \cdot min^{-1}$. Particle sizes employed in erosion testing span from 40 to 312 µm, with variations based on experimental needs.

The study by Zhang *et al.* [8] investigates the effect of various parameters on erosion rates, specifically focusing on different particle sizes, impact angles, and substrate materials. They conducted experiments on first-stage steam turbine components, utilizing ceramic coatings and metal substrates. By varying parameters such as particle size (ranging from 7.5 to 75 mm), impact angle (20–35°), and substrate material, they observed significant differences in erosion rates. This study shows the complex interplay between erosion parameters and coating performance, providing valuable insights for optimizing erosion-resistant coatings in steam turbine applications. The study by Li *et al.* [67] investigates the impact of various parameters on achieving low erosion rates. They specifically focus on the effect of particle size and impact angle on erosion rates of NiCr-Cr_3C_2 coatings applied to FV520B martensitic stainless steel. By varying parameters such as particle size (7, 10, and 14 mm) and impact angle (12, 45, 60, and 90°), they demonstrate how different combinations influence erosion resistance. This study provides valuable insights into optimizing erosion-resistant coatings by considering parameters such as particle size and impact angle.

5.3 Coating process

Determining the most promising coating process depends on various factors such as the specific application, operating conditions, desired properties of the coating, and cost-effectiveness. Table 3 presents several coating processes implicated in SPE, including thermal barrier coating (TBS), atmospheric plasma spray (APS), HVOF, AIP, cathodic arc ion plating, filtered cathodic vacuum arc (FCVA) technique, plasma spray-physical vapor deposition (PS-PVD), plasma-enhanced magnetron sputtering, high-pressure cold spray (HPCS), solid power boronization, and high-velocity air fuel (HVAF).

Based on reviewed studies, coating processes like APS, HVOF, and physical vapor deposition (PVD) show promise in providing effective protection against SPE. APS is utilized in several studies for applying thermal barrier coatings (TBC) and other protective coatings. It offers versatility in coating a wide range of substrates and materials, making it suitable for applications in gas turbines, steam turbines, and other industrial components [65,72]. HVOF spraying demonstrates effectiveness in depositing hard-metal coatings like Cr_3C_2 and tungsten carbide (WC) with cobalt and chromium onto substrates. These coatings exhibit high erosion resistance and are suitable for protecting components in demanding environments [73–76]. Plasma-enhanced magnetron sputtering (PVD) techniques offer precise control over coating thickness and composition, making them suitable for producing wear-resistant coatings like TiAlN. These coatings demonstrate excellent erosion resistance, particularly in steam turbine applications [77,78]. Table 3 highlights the key differences and similarities between the HVOF, APS, and PVD coating processes toward SPE.

Despite their advantages, each coating process has inherent limitations that must be considered. Thermal spray coatings, such as HVOF and APS, rely on line-of-sight application methods, making it difficult to achieve uniform coverage on complex 3D geometries like turbine blades [1]. The rough surface finish of these coatings necessitates post-coating grinding, which can be challenging for intricate shapes and may lead to material removal that compromises the coatings' effectiveness [80,81]. Furthermore, thermal spray coatings often exhibit significant fatigue weaknesses, with reductions in fatigue strength up to 60%, which can reduce their longevity under operational stresses [82]. On the other hand, PVD coatings, while providing precise control over composition and thickness, are limited by their thinness (typically 1–10 μm) and vulnerability to defects like pinholes. These defects can lead to localized corrosion and compromise the integrity of the underlying substrate, limiting the coatings' effectiveness in harsh environments [79,82].

While each process has its advantages and limitations, APS, HVOF, and PVD stand out as promising techniques for developing erosion-resistant coatings. Selection should be based on thorough consideration of application requirements, material properties, and performance expectations. Studies employing processes such as HVAF spraying, as demonstrated by Matikainen *et al.* [68,73] showcase low erosive rates attributed to superior coating density, lower porosity, and improved bond strength. Additionally, coatings produced *via* cathodic arc ion plating, as seen in the study by Liang *et al.* [77], demonstrate excellent erosion resistance due to factors such as high-temperature stability, resistance to SPE, and retention of high hardness even at elevated temperatures.

Based on the reviewed studies, coatings with higher ceramic content or carbide content, deposited using techniques such as HVAF spraying or cathodic arc ion plating, are suggested for achieving optimal erosion resistance. Coatings with higher carbide content and microhardness, such as WC with cobalt and chromium ($WC\text{-}10Co_4Cr$), and those incorporating hard particles like chromium oxide (Cr_2O_3) and boron carbide (B_4C), offer enhanced wear resistance and protection against erosion. Incorporating these materials into composite coatings, as suggested by Dzhurinskiy *et al.* [81], enhances wear resistance, crucial for safeguarding machine components in challenging environments. Furthermore, the selection of coating composition should consider factors such as hardness,

Table 3: Comparison of coating processes for SPE resistance [79]

Aspect	HVOF	APS	PVD
Coating material	Metals, alloys, ceramics	Metals, alloys, ceramics	Metals, alloys, ceramics
Process temperature	Medium to high	High	Low to medium
Particle velocity	High	Medium	Low to medium
Adhesion strength	High	Medium	High
Coating thickness	Thick (100–500 μm)	Thick (100–500 μm)	Thin (1–10 μm)
Porosity	Low	Medium to high	Low
Surface finish	Rough	Rough	Smooth
Application	Wear and corrosion resistance	Wear and corrosion resistance	Hard coatings, decorative finishes
Advantages	Strong adhesion, dense coating	Versatile, can coat complex shapes	Excellent control over coating composition and thickness
Disadvantages	Equipment cost, surface roughness	Higher porosity, lower adhesion	Limited to line-of-sight deposition, higher cost
Effectiveness against SPE	High	Medium	Medium to high

toughness, and resistance to cracking, along with the specific requirements of the application environment.

5.4 Enhancing erosion resistance through advanced and alternative coating technologies

The review highlights the efficacy of coating technology in mitigating erosion rates, particularly SPE, across various materials, notably in aerospace, automotive, and marine industries. Advanced techniques like thermal spray coatings and advanced polymer coatings show promising results in reducing erosion impact on components and structures. These technologies not only shield against erosive forces but also enhance overall durability and lifespan. Furthermore, ongoing research and development in coating technology continuously advances erosion resistance, promising even more effective solutions in the future.

The study by Alajmi and Ramulu [83] aimed to evaluate various coatings, particularly graphene-based ones, for their ability to reduce erosion, specifically SPE. It investigated the effects of coating type, layering, and particle impact angle on wear resistance. Results showed that different coatings alter material wear rates; for example, a single layer of H-146 graphene reduced wear by up to 19%. Increasing layers, such as using two layers of polyurethane, improved wear reduction by up to 38%. Coatings with smoother surfaces exhibited superior resistance to SPE, as illustrated in Figure 11. Graphene-based coatings, particularly when used in single layers or combined with polyurethane, have shown potential for enhancing erosion resistance. In previous studies, improvements of up to 19% in material removal and 8% reduction in erosion depth have been observed with single-layer graphene coatings. Multilayer systems, such as those combining polyurethane and graphene, demonstrated even better performance under certain conditions, with up to 13% improvement in material removal and 16% reduction in scar depth. However, in this study, the level of protection observed was comparable to uncoated samples, suggesting that further optimization or testing may be required to achieve more substantial improvements. The study emphasized that particle impact angle and duration influence coating effectiveness, underscoring the importance of considering operational conditions when selecting coatings.

Similarly, the study by Padmini *et al.* [84] demonstrates the superior erosion resistance of Inconel 738-coated specimens compared to uncoated T11 steel at 700°C, particularly evident at 30 and 90° impact angles. Coated specimens show

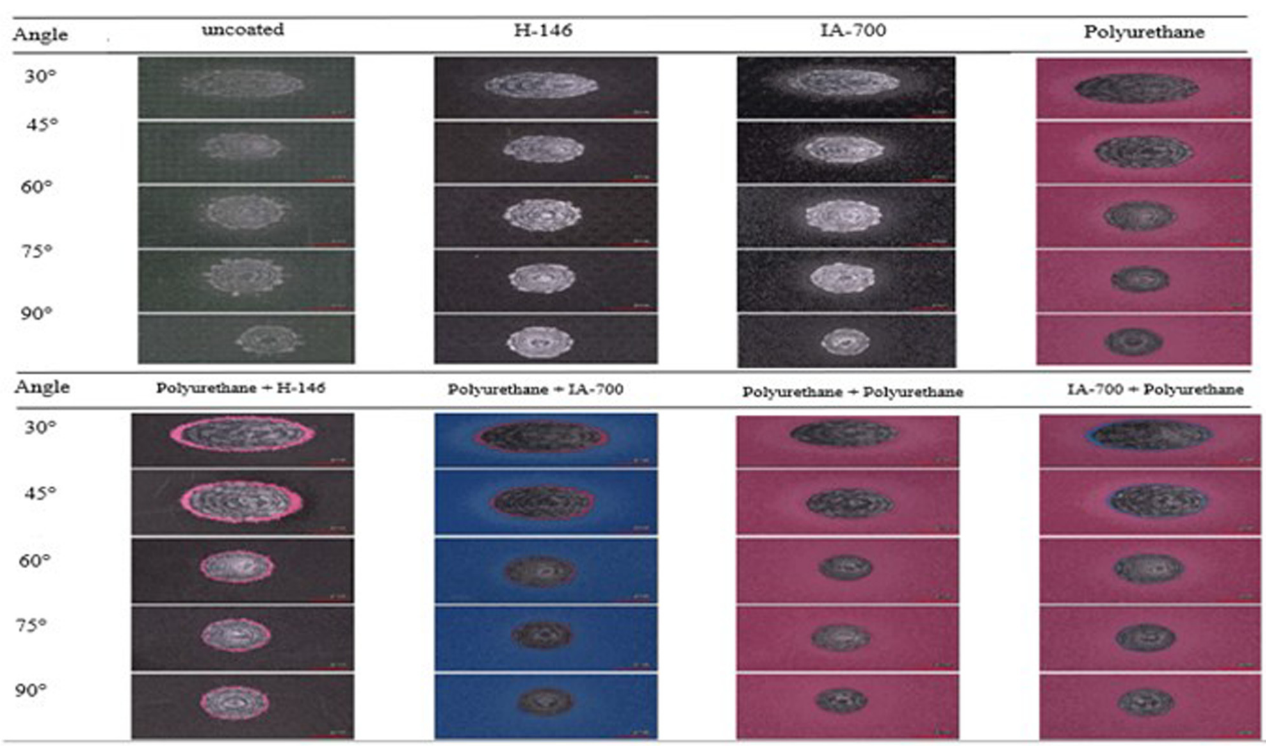

Figure 11: Optical photograph of typical erosion scar shape for uncoated and different coated specimens. Reproduced from Alajmi and Ramulu [83].

up to three times higher erosion resistance, emphasizing the protective benefits of Inconel 738 spray coating in high-temperature environments, such as power plants. The study underscores the coating potential to enhance the durability of critical components like turbines and boiler tubes against SPE. The deposited coating exhibits a defect-free interface, dense structure, and higher hardness, essential for improved erosion resistance against SPE. High-temperature SPE tests reveal that the IN 738 coating outperforms T11 steel, with erosion resistance higher at 30° impact angles but lower at normal impacts due to severe oxide layer fragmentation. Figure 12 provides visual evidence of the eroded surface morphology, illustrating the coatings' effectiveness in mitigating erosion at various impact angles.

Additionally, the study by Yang and McKellar [85] investigated nanolayered and multilayered coatings, particularly CrAlTiN (CrN/AlTiN) and CrAlTiN-AlTiN, for their effectiveness in mitigating erosion damage to engine components. These coatings, with tailored hardness and toughness, significantly outperformed the baseline CrN coating in erosion resistance. The nanolayered CrAlTiN coatings exhibited erosion rates as low as 25 and 16% of the CrN baseline at 30 and 90°, respectively, while the multilayered CrAlTiN-AlTiN coating demonstrated even lower erosion rates. The study aimed to evaluate how altering layer architectures affected erosion resistance, with findings indicating that increasing the number of smaller layers enhanced coating strength against SPE. This research underscores the significant protective impact of layered coatings on engine parts exposed to abrasive wear, offering insights into optimizing coating composition for enhanced durability and performance in erosion-prone environments.

Prasanna *et al.* [86] investigated the efficacy of HVOF coatings in mitigating erosion in turbine alloys. They tested Stellite-6, alumina-CoCrAlTaY, and Cr_3C_2-NiCrNiCrAlY coatings on titanium alloy, cobalt-based superalloy, and special steel substrates, subjecting them to silica sand particles at

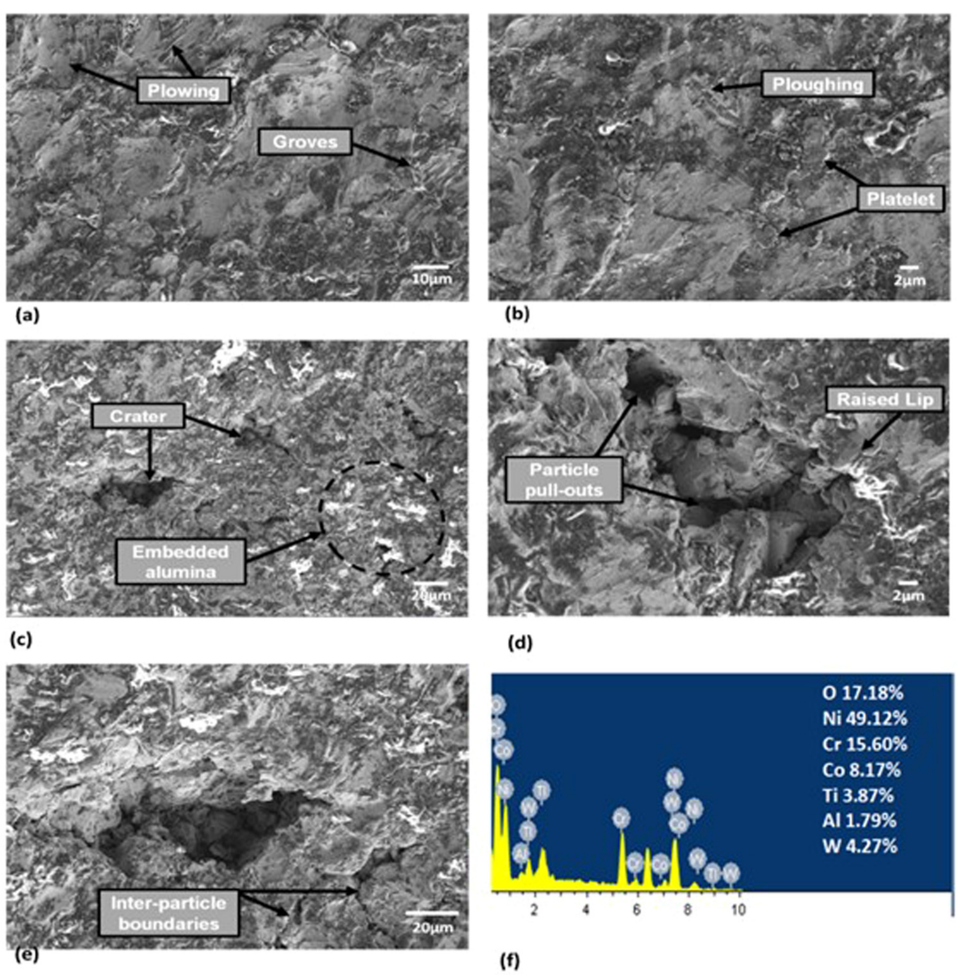

Figure 12: Erosion morphology of IN 738 coating at 700°C: (a and b) 30°, (c–e) 90° impact, and (f) EDX analysis. Source: by Padmini *et al.* [84].

varying angles and velocities. Stellite-6 showed the lowest wear rate, especially at a 30° impact angle, highlighting its superior resistance to damage. The study emphasizes the importance of coating selection based on operational conditions, with HVOF coatings offering promising protection against erosive wear, potentially prolonging turbine part lifespan.

Matikainen *et al.* [68] compared Cr_3C_2-based coatings sprayed *via* HVOF and HVAF methods for abrasion, dry particle erosion, and cavitation erosion resistance. Coatings with higher carbide content exhibited lower erosion rates, particularly evident at a 90° impact angle, emphasizing resistance to particle penetration. HVAF-sprayed coatings outperformed HVOF-sprayed ones, being harder, tougher, and more resistant to various wear types. Cr_3C_2-50NiCrMoNb coatings excelled in resisting cavitation erosion, while Cr_3C_2-37WC-18NiCoCr coatings balanced wear resistance and toughness well. The study duration for erosion testing was 6 h for each sample. Figure 13 illustrates significantly higher resistance of HVAF sprayed coatings, especially CW and W coatings, attributed to higher particle velocities resulting in increased peening and lower carbide dissolution, reducing the formation of brittle heterogeneous coating structures and poor interlamellar bonding.

Chemical vapor deposition (CVD) is emerging as a highly effective alternative coating technology for addressing both SPE and WDE. CVD coatings are recognized for their ability to form uniform, dense, and adherent layers on complex geometries, making them particularly suitable for turbine blades and other intricate components. For instance, CVD W/WC coatings, composed of WC nanoparticles in a metal tungsten matrix, have demonstrated remarkable fracture toughness and high hardness [87,88], providing exceptional protection against both WDE and SPE. Testing has shown that these coatings significantly outperform uncoated samples and traditional protective materials, exhibiting negligible damage even after prolonged exposure to erosive conditions [89].

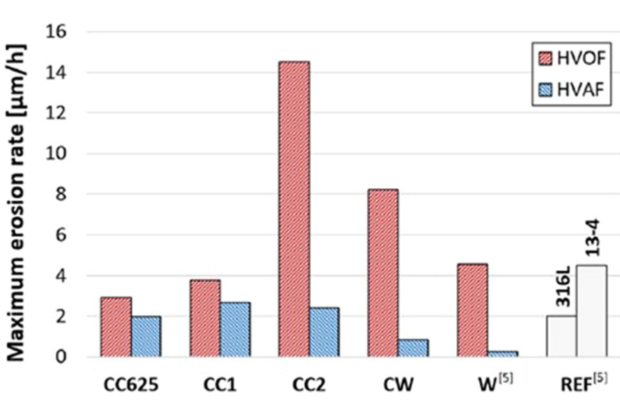

Figure 13: Maximum erosion rates after cavitation erosion test. Source: Matikainen *et al.* [68].

While CVD coatings offer substantial benefits, it is worth noting that previous reviews have highlighted a limited number of studies specifically applying CVD technology for SPE protection. Research on the application of CVD coatings for SPE has been relatively scarce compared to their use in WDE, suggesting a gap in the literature that could benefit from further exploration [90]. Despite this, the available evidence underscores the potential of CVD coatings in enhancing the durability and performance of metal components across various industrial applications. The uniform, pore-free nature of CVD coatings contributes to their effectiveness against the impacts of solid particles, thereby extending the service life of the equipment. Additionally, CVD-grown graphene coatings have been shown to enhance corrosion resistance significantly, further broadening the protective capabilities of CVD technology [91].

In the context of nanotechnology, recent advancements in nanocomposite coatings, particularly those incorporating boron carbide (B_4C) nanoparticles, have shown promise in improving erosion resistance. Studies have demonstrated that the addition of nano-sized B_4C particles to aluminum matrix composites enhances hardness and tensile strength, which are critical properties for resisting erosion [92]. These findings align with the broader trend of utilizing nanotechnology to develop coatings with superior mechanical and corrosion-resistant properties, further supporting the potential of advanced coatings in mitigating SPE and WDE challenges.

6 Summary discussion

Steam turbines play a vital role in energy conversion, with meticulously designed blades spanning LP, MP, and HP sections to optimize efficiency, durability, and strength. Despite this, threats like fatigue, corrosion, and erosion, particularly SPE, pose significant challenges, hastening blade degradation. SPE prevalent in HP regions gradually wears down blades, necessitating ongoing research on materials and coatings for protection. From 2013 to 2023, there has been a significant growth in research related to erosion, as evidenced by the steady rise in publications, which increased by approximately 133%. In 2013, the field produced around 150 publications, and by 2023, this number had surged to 350. This growth highlights the growing interest and relevance of erosion studies.

The blades of steam turbines are susceptible to various failure modes, including thermal stress, mechanical stress, vibration effects, corrosion, erosion, fatigue, and creep. Thermal stress, induced by temperature variations, can lead to deformation and cracking, while mechanical stress from steam pressure and centrifugal forces contributes to blade fatigue. Additionally, corrosion, often triggered by corrosive fuel elements, can result in alkali metal formation and subsequent blade corrosion. Fatigue failure occurs when cyclic stresses exceed material fracture toughness, exacerbated by factors like material quality and operating conditions. Creep, the gradual distortion of materials under high temperatures and stress poses ongoing risks. Erosion, prominently affecting turbine blades, results from the abrasive action of suspended particles in steam flow, leading to surface deterioration and performance loss. Notably, erosion emerges as a leading degradation mechanism, alongside erosion corrosion, underlining the importance of proactive maintenance and optimization efforts to mitigate blade failures and ensure turbine performance reliability.

SPE poses a significant threat to HP steam turbine blades, particularly in regions like control valve stems and first-stage blades. During operation, solid particles carried by steam collide with blade surfaces, leading to erosion. Understanding SPE mechanisms is critical, with factors like particle type, size, velocity, and impact angle influencing erosion. Research by Laguna-Camacho *et al.* [37] and Shitole *et al.* [36] highlights material behaviors under erosive conditions, emphasizing the importance of particle characteristics and impact angles. Additionally, turbine blade design and protective coatings significantly impact erosion resistance, as demonstrated in studies by Chen *et al.* [43] and Leyzerovich [46]. Materials like steel, especially when treated, exhibit enhanced resistance to erosion, while advanced computational modeling optimizes blade designs for better performance. The complexities of SPE warrant thorough investigation to develop effective mitigation strategies and enhance turbine longevity and efficiency.

SPE significantly impacts the operation of steam turbine blades, influenced by multiple factors, including particle velocity, impact angle, substrate material, type of erosive particle, and temperature. Higher particle velocities generally correlate with increased erosion rates, emphasizing the need to minimize these velocities during turbine operation. Additionally, the angle of particle impact is a pivotal factor in determining the severity of erosion. Particles striking at near-normal angles (90°) tend to generate substantial material removal compared to those impacting at shallower angles (less than 30°). At near-normal angles, the particles deliver a more direct force to the surface, leading to increased material displacement and, thus, a higher erosion rate. Conversely, at shallow angles, particles may merely graze the surface, resulting in less significant damage [74,98]. The relationship between impact angle and erosion is influenced by particle size: smaller particles at shallower angles result in lower erosion rates, while larger particles at steeper angles cause more significant damage. However, this relationship can vary depending on the material type for instance, in ductile materials, maximum erosion often occurs at shallow angles (30°), while in brittle materials, near-normal angles (90°) typically lead to more significant damage. Higher temperatures correlate with accelerated erosion rates, highlighting the significance of addressing temperature effects.

The impact of temperature on erosion further complicates this relationship, as it is primarily associated with metal softening at elevated temperatures [99]. In steam turbines, components are routinely exposed to high thermal conditions, causing metals to undergo a reduction in hardness due to phase changes and thermal activation of dislocation movement. This softening increases the susceptibility to erosion, as the material can deform more readily under the impact of eroding particles. Consequently, the wear rate of the material may increase significantly, making it more vulnerable to damage during operation. Materials with superior hardness and resistance, such as AISI 420 stainless steel, exhibit lower erosion rates compared to softer materials like copper [37]. This phenomenon underscores the importance of optimizing impact angles and considering temperature as a critical factor in erosion studies, especially for materials used in high-temperature applications like steam turbines [100].

Additionally, understanding the characteristics of erosive particles like SiC, quartz, and alumina is crucial for minimizing erosion rates. The choice of erosive particles and material samples in numerous research may not correctly represent actual circumstances for steam turbines, resulting in distorted outcomes and deceptive trends. Softer metals such as copper, which exhibit greater ductility, do not undergo the brittle failures observed in harder turbine materials, resulting in lower erosion rates at 90° impact angles, in contrast to turbine blades fabricated from materials like stainless steel [31,101]. Likewise, the employment of excessively hard particles such as alumina or SiC, which are improbable in turbine environments, skews the significance of results, as actual turbines are majorly subjected to particles like quartz or iron oxides [31,41,101]. Inappropriate material selections can substantially affect erosion predictions and trends, resulting in an inaccurate depiction of SPE during actual turbine operations. Consequently, research employing more realistic mixtures of erosive particles and tougher metals, such as stainless steel in conjunction with quartz or iron oxides, will more accurately replicate actual turbine settings and provide more dependable insights for minimizing SPE [3,31,41,101]. Optimizing these parameters is vital for minimizing erosion rates in turbine blades and preserving turbine component integrity and performance.

Figure 14 illustrates the distribution of publication years for studies related to SPE in steam turbine blades. It highlights specific data points such as substrate material, erosive particle, particle size, particle flow rate, temperature, impact speed, and angle. Each bar color on the graph represents parameter studies on SPE. The presence of specific materials used as substrate material and erosive particles is indicated by color-coding in light yellow and light green, respectively, within each bar. This visualization provides insights into the temporal distribution of research efforts in the field of SPE in steam turbine blades and highlights the variability in parameters across different publication years. Between 2013 and 2015, experiment-based studies accounted for approximately 30% of the research. In contrast, from 2020 to 2023, simulation and computational data approaches became dominant, comprising around 70% of the studies. The parameters of impingement angle and impact speed emerged as key research focuses from 2013 to 2023, underscoring their crucial role in understanding erosive wear mechanisms across both experimental and simulation-based investigations. The graph integrates computational data, highlighting the limited number of publications based on experimental studies compared to the more frequent occurrence of simulation-based studies. While computational models are powerful tools, they may not always capture the full complexity of real-world scenarios due to simplifications and assumptions made during model development. By comparing these two approaches, existing gaps in the literature can be addressed while acknowledging the strengths and limitations inherent in each method. This integrated perspective enhances understanding of erosion in steam turbine applications and informs future research directions.

Recent advancements in coating technologies offer promising solutions for mitigating SPE in various industries, including aerospace, energy, and manufacturing. Coating compositions vary widely, ranging from YPSZ to boride coatings, with application methods including APS, HVOF spraying, and plasma-enhanced magnetron sputtering (PVD). These coatings exhibit diverse erosion resistance properties influenced by factors such as material hardness, porosity, microstructure, and resistance to cracking. Experimental conditions simulate operational environments, with studies examining parameters like particle size, impact angle, substrate material, and temperature to optimize erosion resistance. Notably, coatings with higher ceramic or carbide content, applied using techniques like HVAF spraying or cathodic arc ion plating, show promise in achieving optimal erosion resistance. Additionally, layered coatings, such as CrAlTiN and CrAlTiN-AlTiN, demonstrate superior erosion resistance compared to baseline coatings. Overall, investing in advanced coating technologies holds significant potential for extending component lifespan and enhancing performance in the face of SPE challenges across diverse industrial sectors.

The graph from Figure 15 illustrates various coating processes and parameters investigated from 2013 to 2023,

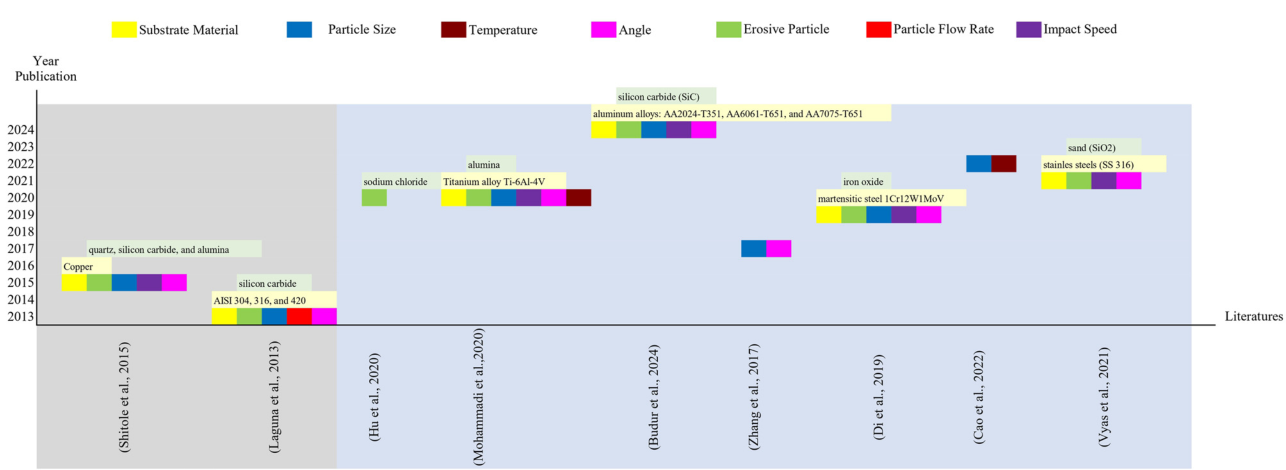

Figure 14: Distribution of research on SPE factors in steam turbine blades (2013–2023).

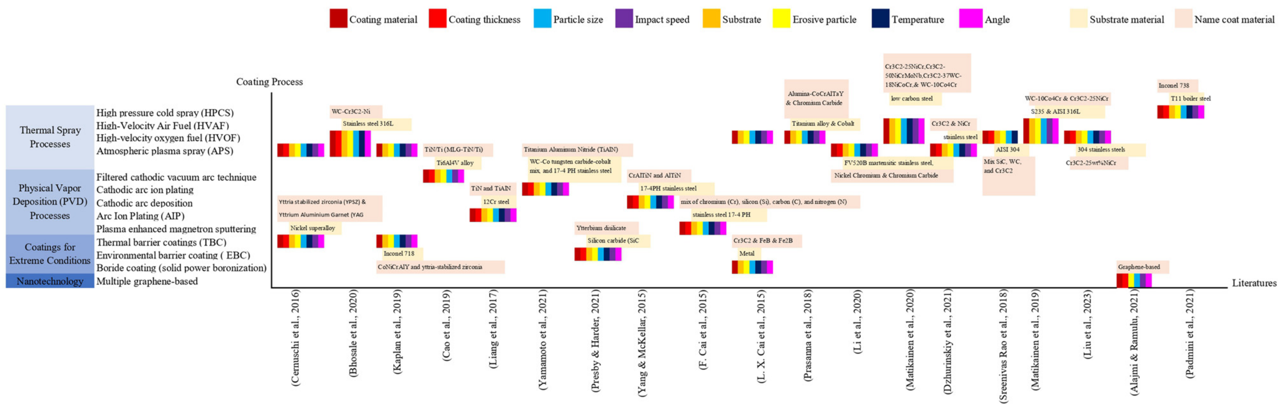

Figure 15: Coating process distribution analysis for SPE (2013–2023).

revealing key trends and gaps in research. From 2014 to 2023, thermal spray processes dominated coating studies, representing about 50% of the research, while PVD accounted for roughly 30%. Coatings designed for extreme conditions comprised around 20% of the studies, particularly increasing in prominence post-2018, highlighting the growing demand for advanced coatings in harsh environments.

Thermal spray processes, specifically HVOF, APS, and HVAF, are thoroughly researched and often used for materials such as stainless steels and titanium alloys. Processes such as cathodic arc deposition and AIP, which are part of the PVD techniques, are commonly used. These processes often involve the use of materials like YPSZ and TiAlN, which are frequently studied. Coatings for extreme conditions, such as TBC and environmental barrier coatings, focus on materials like SiC and Inconel alloys. Current nanotechnology research emphasizes the use of graphene-based coatings, demonstrating a growing preference for advanced materials. While APS, HVOF, and PVD remain promising techniques for developing erosion-resistant coatings, addressing their limitations is crucial for optimizing their application. Furthermore, CVD coatings, particularly those made from W/WC and graphene, present an advantageous alternative that warrants further exploration, especially in the context of SPE, to provide robust protection against mechanical and chemical degradation in demanding environments.

Essential factors for optimal performance include the type of coating material, the thickness of the coating, and the size of the particles. Impact speed, substrate, erosive particle, temperature, and angle are also studied, though less frequently. Studies have shown a substantial surge after 2015, indicating a rising interest in this particular topic. Contributions from various authors are noted across the years. Processes like HPCS and plasma-enhanced magnetron sputtering are not adequately represented. Although the coating material and thickness have been extensively researched, there is a need for more complete research on characteristics such as impact speed and erosive particles. Further investigation is necessary for advanced applications such as environmental barrier coatings and boride coatings. Finally, incorporating more recent research would guarantee the inclusion of the most current improvements. This review emphasizes the wide range of research conducted on coating processes and factors, while also identifying certain areas that require more exploration to improve industrial coating solutions.

The novelty of this article lies in its key contributions to the field of SPE in steam turbine blades. It highlights a 133% rise in erosion-related research from 2013 to 2023, reflecting the growing importance of this topic. The article critically evaluates the inappropriate selection of materials and particles in many studies, advocating for more realistic combinations, such as stainless steel with quartz or iron oxide, to improve erosion predictions. Additionally, it compares experimental and computational approaches, outlining their strengths and limitations. Finally, it identifies research gaps in coating technologies, emphasizing the need for further exploration of CVD coatings and underrepresented processes like HPCS. These insights provide guidance for future research to enhance turbine blade durability.

7 Conclusions and future direction

SPE is more complex than it may appear at first glance. Addressing SPE in steam turbine blades requires a multidisciplinary approach, integrating insights from material science, fluid dynamics, and engineering design. By staying abreast of advancements in materials, coatings, and design methodologies, turbine maintenance and operation practices can be optimized to mitigate the adverse effects of SPE, thereby prolonging turbine lifespan and improving overall performance. For the past decades, hundreds of brilliant researchers have engaged vigorously in erosion science. After reviewing the resulting body of research, several reflections on the past and future of erosion research can be made:

- The failure of steam turbine blades can stem from a multitude of factors including thermal stress, mechanical stress, corrosion, erosion, fatigue, and creep. These issues arise from the harsh operating conditions turbines endure, exacerbated by corrosive substances in fuels and abrasive particles in steam flow. Research emphasizes the detrimental impact of erosion, erosion–corrosion, and fatigue on blade integrity and performance, highlighting the urgent need for proactive maintenance and optimization strategies to ensure consistent turbine operation over time.
- SPE poses a significant threat to HP steam turbine blades, impacting both structural integrity and operational efficiency. Understanding SPE mechanisms, including particle characteristics, impact angles, and material properties, is crucial for effective mitigation. Research highlights the importance of material selection, design optimization, and protective coatings in enhancing erosion resistance. By comprehensively addressing these factors, turbine lifespan can be prolonged, and operational performance optimized, ensuring reliable and efficient turbine operation.
- The effects of SPE on steam turbine blades are influenced by factors such as particle velocity, impact angle, substrate material, type of erosive particle, and temperature. Lower particle velocities, higher impact angles, materials with superior hardness, and erosion-resistant particles like SiC help minimize erosion rates. Maintaining optimal temperatures further mitigates SPE damage. Understanding and optimizing these parameters are essential for effective SPE mitigation, ensuring prolonged turbine lifespan and enhanced operational efficiency. Future research should capitalize on advancements in computational modeling, materials science, and interdisciplinary approaches to enhance erosion-resistant materials and coatings. Emphasizing sustainability and efficiency, there is potential to explore eco-friendly materials and coatings, particularly for renewable energy technologies. Interdisciplinary collaboration and innovative technologies will continue to advance SPE research and develop robust mitigation strategies for various engineering applications.
- Thermal spray processes such as HVOF, APS, and HVAF are extensively researched for materials like stainless steels and titanium alloys, while PVD techniques like cathodic arc deposition and AIP often use YPSZ and TiAlN. Coatings for extreme conditions focus on SiC and Inconel alloys, with a growing emphasis on graphene-based coatings in nanotechnology. Key performance factors include coating material, thickness, and particle size, though impact speed, substrate, erosive particle, temperature, and angle related to SPE are less studied. Comprehensive research on impact speed, erosive particles, and advanced applications like environmental barriers and boride coatings is needed, along with incorporating recent studies to capture the latest advancements.

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