International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 09, RTMSE-2026

Role of Surface Treatment for Enhancing Resistance to Degradation: An Outline

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***Abstract*—Engineering systems operating under severe conditions, such as thermal power plants, turbines, cement industries, and aerospace applications, experience progressive deterioration due to solid particle erosion (SPE), wear, and erosion-corrosion interactions. Surface modification was proposed as an efficient method to improve the degradation resistance without influencing bulk properties. The approaches of surface modification, such as hard facing, thermal spray coating, friction stir processing, advanced nano-structured and multilayer coatings, are evaluated in this paper. Special attention is given to relating the surface micro-morphology to the prevailing erosion mechanisms at different impact angles, particle velocities, temperatures, and particle sizes. Surface-treatment comparisons of microstructure, erosion behavior, and performance trends are presented in a single master table, whereas the parametric assessment reveals the inadequacy of hardness-based design approaches. This review shows that erosion resistance is not solely determined by surface hardness but also by coating architecture, phase distribution, toughness, and resistance to crack propagation. More advanced multilayer and hybrid surface modifications are promising, but their efficiency largely depends on the application. Recommendations are provided for selecting durable surface treatments resistant to erosion, and new areas of research are suggested.**

Keywords - Degradation, hardfacing, coating, heat treatments, microstructure, hardness

I INTRODUCTION

In industrial applications, the working span of mechanical components is strongly affected by harsh operating conditions that progressively degrade material properties and functional performance. Over the period of their service life, materials employed in thermal power plants (coal-based), mining industries, spacecraft structures, hydraulic turbines, and rolling mills are subjected to severe mechanical, chemical, and thermal conditions that lead to material degradation [1-3]. Among these, boiler tube failure remains a critical issue for boiler designers, as the service life of the entire system is predominantly relied on the strength and endurance of its components, particularly the boiler tubes [4-6]. The high temperatures in the boiler house (greater than 500°C) leading to material to be removed from its surfaces. Erosion and corrosion are the primary degradation processes that cause boiler tubes to fail prematurely under these operating conditions [7].

Degradation of industrial components may occur in many forms, including slurry erosion, cavitation erosion, abrasive or adhesive wear, fatigue wear, erosion-corrosion, and solid particle erosion. During such degradation, which may be shown in Figure 1, component surface comes into contact with other moving parts or particles moving through the system [8]. Turbine blades in hydraulic power plants are particularly susceptible to cavitation erosion, which is caused by the collapse of vapor bubbles generated during high pressure flow. Frequent formation and collapse of these bubbles form cavities which gradually erode and diminish the working span of blade [9].

The process of abrasive wear takes place when a irregular or hard surface slices and scratches softer materials [10-12]. Although the mechanism of degradation in solid particle erosion is the same, failure in this instance is brought by the high velocity, continuous impingement of solid particles. Pulverized coal burner nozzles in coal-fired boilers are prone to severe erosion caused by impacts between combustion particles carried by high-velocity air. Important factors influencing erosion rates are surface ductility, impact angle and velocity, and working temperature. Pitting, cracking, and brittle fracture are more prevalent in hard and brittle surfaces at normal impact angles, whereas ploughing action removes the majority of material from ductile materials at low impact angles [4, 13]. Higher temperatures, particle velocities, and environments that combine erosion, corrosion, and oxidation have made the physical requirements of engineering components more demanding in recent years. Components in the cement, aerospace, and thermal power generation industries commonly undergo solid particle erosion at high velocities and temperatures more than 500°C [14-16]. Degradation brought on by erosion has serious economic

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 09, RTMSE-2026

consequences. Whenever plants are shut down to replace eroded boiler components, erosion-related failures account for 50-75% of power plant downtime [17]. In previous studies, in thermal power plants, replacing boiler tubes and heat exchangers accounts for roughly 54% of overall production expenditures [7]. Incorporating recently developed materials which are less prone to degradation is one viable solution, but the component design becomes much more difficult and expensive. For components like boiler tubes, which are primarily surface-damaged, enhancing the surface properties without impacting the cost of the material is a more feasible and economical way for enhancing the service life.

In this context, conventional material selection criteria are no nevertheless effective to ensure reliable performance over an extended period of time. In light of these studies, it is now evident that surface hardness solely cannot govern erosion resistance. Instead, the performance of surfaces is controlled by a combination of factors such as coating microstructure, phase composition, coating formulation, particle characteristics, and erosion parameters such impact velocity [18-20]. In order to prevent material degradation, surface-mediated advanced treatment technologies such as carbide-based thermal spray coatings, boride-rich overlays, multilayer and nanostructured coatings, and hybrid techniques of surface processing with coating deposition have attracted a lot of attention [21-24]. However, these methods have limitations involving coating thickness, brittleness, thermal stability, high angles, or large particle impact.

Therefore, a thorough understanding of the relationship between surface treatment methods and the ensuing microstructural change, as well as the actual mechanisms of failure under load, are essential for the effective design of highly erosion-resistant components.The current contribution offers an analysis of the most recent developments in surface-treatment techniques established to increase resistance against erosion-dominant environments for industrial and energy uses in this vast landscape.

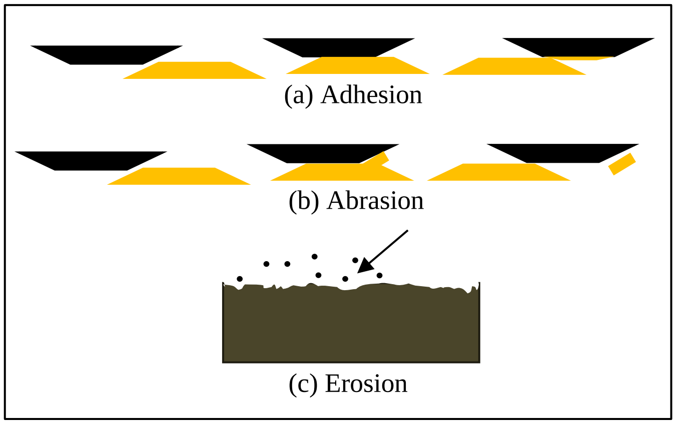

Figure 1: Material removal mechanism through different techniques.

II SURFACE TREATMENTS AS REMEDIAL TO DEGRADATION

Plenty of studies have already been performed to mitigate component material deterioration. The many techniques and materials used to boost resistance to degradation are reviewed in the literature review (Figure 2). Common techniques for enhancing the inherent properties of component material surfaces include surface treatments including heat treatments and surface overlaying [25]. The original material undergoes heat treatments to eliminate the stresses generated during casting or fabrication. Parent material may undergo normalizing, carburizing, nitriding, quenching, and annealing heat treatments [26-28].

A. *Hardfacing and weld-based surface overlays*

Hardfacing remains the most commonly used surface engineering technique for heavily eroded and worn components. In hardfacing, a wear-resistant material layer is deposited on the substrate surface using fusion techniques such as gas metal arc welding, shielded metal arc welding, plasma transferred arc welding, and laser spraying. Thick, difficult to break protective layers are formed with tight metallurgical bonding during hardfacing, making it suitable for high temperature and high-load applications. Recent studies revealed the degradation resistance of hardfaced layers is largely determined by the number, distribution, and orientation of hard phases. Carbide-rich overlays, such as those containing extensive chromium and tungsten carbides, have high surface hardness and resistance to low-angle erosion, dominated by cutting and plowing mechanisms [29-31]. However, these overlays are prone to fracturing and chipping under standard impact conditions due to a lack of toughness. The most important boride based overlay is iron boride, which consists of Fe_2B phases and exhibits resistance to low and high impingement angles due to its tight microstructure and hardness [8, 19]. According to studies, single-phase Fe_2B is more stable than duplex FeB-Fe_2B systems because crack propagation along the brittle FeB phase can trigger coating failure. Minimizing and optimizing stirring rather than vitrification are important for making erosion resistance predictive.

B. *Thermal spray coatings*

Thermal spray coatings play a significant role in improving surface wear resistance while maintaining the substrate's bulk composition. Techniques, like high-velocity oxy-fuel (HVOF), high-pressure air fuel (HVAF), atmospheric plasma spraying (APS), and detonation spraying, allow for the deposition of hardmetal coatings with a thickness of 100–500 µm, typically deposited using the above-mentioned methods [21, 32]. HVOF and HVAF processes are characterized by greater erosion resistance, associated with lower porosity, improved splat cohesion, and reduced decarburization. Carbide-based coatings, including WC-Co, WC-CoCr, and Cr_3C_2-NiCr, are commonly used for erosion protective applications in turbines, boiler tubes, and industrial fans. Experimental research has demonstrated that erosion

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 14, Issue 09, RTMSE-2026

resistance is strongly dependent on carbide particle size and carbide retention, as well as binder distribution [33, 34]. Fine-dispersed WC particles improve erosion resistance and point-of-impact toughness by increasing energy dissipation and crack stoppage through uniform particle distribution. At the same time, coarse carbides can break or spill out as the attack angle increases during erosive wear.

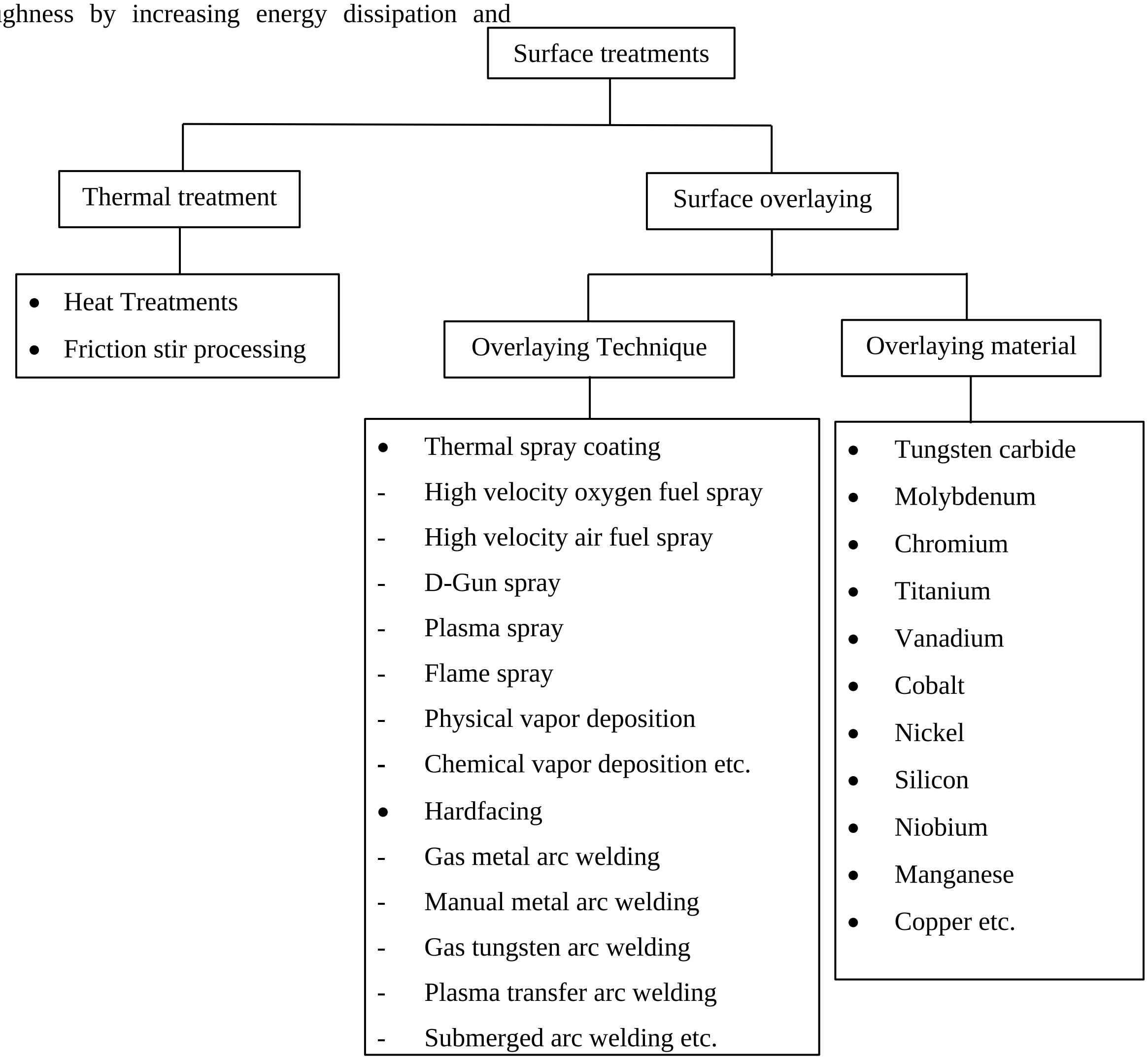

Figure 2: Techniques and alloying elements used for improvement to the surface degradation resistance.

Thermal spray coatings erode in a complex manner at high temperatures owing to the combined effects of oxidation, softening of metallic binders, and phase transformations [15, 35]. In high-temperature erosion, HVOF coatings have been found to perform better than APS coatings, owing to their denser microstructure and higher inter-splat adhesion. Nevertheless, the low thickness of thermally sprayed coatings may not withstand long-term erosion from large or rebounding particles and may experience mechanical failure, leading to substrate exposure [36, 37]. The effect of impact angles ranging from 15° to 90°, particle velocities ranging from 0.3 km/s to 5.15 km/s, temperature (298 K), and relative dimensions of the KyShield coated surfaces is synthesized in tensile properties at RT, as well as resistance to erosion offered against Oblique impacts with respect to RHA steel under identical testing conditions is depicted in TABLE 2.

C. *Advanced nano-structured and multilayer coatings*

Recent progress in surface engineering has generated new classes of nanostructured and multilayer coating systems proposed to surpass the performance of traditional hard coatings. Multilayered designs such as Ti/TiN, TiAl/TiAlN, and nanocomposite coatings containing TiAlSiN or CrSiCN phases, combining high hardness with increased toughness and stress accommodation, have shown good erosion resistance [20, 23, 24]. In such coatings, erosion resistance is linked to mechanical indicators including the H/E and H3/E2 ratios rather than hardness per se [38-40]. The multilayer interfaces serve as effective barriers to crack propagation, and

International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
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the nanoscale phase structure enables controlled plastic deformation under particle impact. Experimental studies have shown that, at high temperatures used in gas turbine and compressor blade applications, these coated systems provide 5 to 15 times greater erosion resistance than uncoated substrates.

MAX-phase coatings, for example, such as Cr_2AlC, have also attracted interest as erosion-resistant materials because of the combination of ceramic hardness and metallic damage tolerance [41]. The latter coatings undergo gradual erosion, with slow material loss and no catastrophic brittle fracture, resulting in a longer service life during solid-particle erosion.

TABLE 1: EXPERIMENTAL STUDIES REGARDING SURFACE MODIFICATIONS

Surface treatment / technique	**Substrate**	**Coating / treatment material**	**Key microstructural feature**	**Dominant degradation / erosion mechanism**	**Performance trend**	**Ref.**
Flame hardening	Low carbon Cr steel	Heat-treated surface	Residual stress–controlled martensitic layer	Thermal stress–assisted wear	Improved surface hardness; stress sensitive	[42]
Heat treatment	AA7075 alloy	Solutionizing + aging	Precipitation-hardened microstructure	Erosion via plastic deformation	Harder alloys show higher erosion	[43]
Multilayer hardfacing	ASTM A36 steel	Cr-rich / W-rich carbides	Complex carbide networks	Abrasive wear	Carbide-rich layers show superior resistance	[29]
Hardfacing (GMAW / SMAW)	Low carbon steel	Fe-Cr-C-Nb alloy	Fine carbides in martensitic matrix	Abrasion and erosion	Improved wear resistance with Ti addition	[44]
Boride-based overlays	Carbon / alloy steels	Fe_2B / FeB borides	Compact single-phase boride	Crack-resistant erosion	Stable at low and high angles	[8, 45]
Thermal spray coating	SS304	WC-10Co-4Cr	Dense splats, low porosity	Brittle chipping at high angles	High resistance at low angles	[15, 21]
Thermal spray coating	AISI 304	Cr_3C_2–NiCr	Lamellar structure	Brittle fracture	Moderate erosion resistance	[46]
HVOF / HVAF coating	Steel substrates	WC-based hardmetals	Fine WC particle distribution	Cutting and micro-chipping	Superior to APS coatings	[32, 33]
Nano-WC composite coating	AISI 304	WC–Co–Cr + nano WC	High carbide retention	Ductile-to-brittle transition	Increased hardness and erosion resistance	[34, 47]
Multilayer nitride coating	Ti alloys	Ti/TiN	Stress-absorbing multilayers	Controlled plastic deformation	5x-15x erosion resistance improvement	[20, 23, 24]
Nanocomposite coating	IN718	Cr_2AlC (MAX phase)	Damage-tolerant layered structure	Progressive erosion	Extended coating life	[41]
Friction stir processing	Mg / Al alloys	Grain-refined surface	Ultrafine equiaxed grains	Adhesive/abrasive wear	Improved wear resistance	[12]
Hybrid coating + FSP	Low carbon steel	WC-based MMC	Uniform particle redistribution	Reduced ploughing	Enhanced abrasion resistance	[48]

D. *Friction Stir Processing and hybrid approaches for surface modification*

Friction Stir Processing (FSP) has emerged as a solid-state surface modification process and is receiving increasing attention for refining the grain structure and improving surface mechanical properties without introducing associated defects. Friction Stir Processing has been reported to drastically decrease grain size, increase hardness, and improve resistance against cavitation and slurry erosion, especially in aluminum and magnesium [12, 49, 50]. It has recently been reported that FSP can also be used for post-treatment of thermally sprayed or cold-sprayed coatings [48]. Although FSP is beneficial for distributing reinforcing particles and reducing inter-splat defects, it can increase porosity or even cause partial decarburization unless processing conditions are well optimized. However, hybrid techniques such as controlled FSP-coated deposition may be a promising way to achieve a compromise between hardness, strength, and erosion resistance.

A summary of surface treatment methods reported in the literature to improve degradation resistance under erosive and wear-dominant conditions is listed in TABLE 1. Unlike individual experimental synopses, the table provides the substrate type, surface modification methodology, resulting microstructural characteristics, predominant modes of erosion, and overarching performance trends.

The comparison indicates that surface technologies that enhance hardness alone, such as carbide-based hardfacing and thermal spray coatings, exhibit excellent wear resistance under low incident-angle erosion conditions but can eventually fracture or chip at normal impact angles. On the other hand, boride over-layers and state-of-the-art multilayer coatings exhibit greater stability owing to their denser microstructure and higher resistance to crack propagation. It can also be seen from the table that advanced nanostructured and multilayer coatings exhibit better erosion resistance than coating hardening alone, through the optimal combination of coating architecture and stress accommodation capacity. Hybridisation via coating deposition followed by post-treatment methods, such as FSP, is also promising for finding a trade-off between hardness/toughness and durability. In summary, the comparison highlights that selecting an appropriate surface treatment is an application-specific process that should be grounded in a sound understanding of erosion mechanisms, microstructural responses, and service conditions.

III CHALLENGES AND LIMITATIONS OF SURFACE TREATMENT TECHNIQUES

Despite the progress made, no single surface treatment method provides all-around protection against dent formation across all erosion conditions. Coatings of carbides and hardfaced layers, while effective at low impingement angles, can be subject to brittle fractures and chipping under common impact erosion [51, 52]. Thermal sprays are limited to relatively thin coatings, which can fall short under prolonged exposure to high-velocity or large-particle environments. At higher temperatures, the reduced performance is complicated by oxidation and thermal softening. However, oxide scale formation can sometimes lower erosion rates, but this may be offset by the beneficial rate-accelerating effect of scale spallation in cyclic environments. Needless to say that, in many cases, hard coatings fail to be applied against the millimeter-scale rebounding particles often present insteam turbines and industrial fan environments, as suggested by results obtained from studies where the mechanical sequestration of said particles was more efficient than coating only the surface [36, 53, 54].

Advanced multilayer and nanoscale-structured coatings achieve high reflectivity at the laboratory scale. Nevertheless, their long-term stability, repairability, and cost-effectiveness still pose challenges for large-scale use in an industrial environment [22, 55]. Such constraints underline the importance of surface engineering strategies, which are designed specifically for applications and predicated on a sound apprehension of erosion mechanism(s), material behaviour, and service conditions.

TABLE 2 summarizes the effects of key parameters, including impact angle, particle velocity, temperature, and particle size, on the erosion performance of surface-engineered materials. The table also illustrates that the erosion response is very sensitive to operating conditions, and the performance of a given surface treatment cannot be universally applicable without accounting for application-dependent variables. From TABLE 2, it is clear that the impact angle is pivotal in governing the erosion mechanisms. Most ductile materials lose material to a greater extent at oblique angles, whereas brittle and carbide-rich coatings are more vulnerable under normal impacts. Likewise, particle velocity and size play a significant role in the transition from plastic deformation-controlled erosion to brittle fracture and chipping, especially for hard coatings.

The table also shows that, with increasing temperature, complex reactions can occur involving oxidation, phase transformations, and softening of the binder phases, leading to both increased and decreased erosion depending on the material chemistry and microstructure. These results indicate that surface treatment methods should be selected based on knowledge of erosion parameters rather than solely on hardness increase.

TABLE 2: EFFECT OF EROSION PARAMETERS ON SURFACE TREATMENT PERFORMANCE

Erosion parameter	Observed effect	Design implication	Ref.
Impact angle	Ductile erosion peaks at low angles; brittle erosion dominates at normal angles	Select coating according to erosion mode	[38, 51]
Particle velocity	Threshold velocity induces brittle fracture	Avoid excessive surface hardness	[35, 52]
Temperature	Oxide scale formation alters erosion rate	Consider oxidation-assisted protection	[14, 15]
Particle size	Large rebounding particles defeat hard coatings	Combine coatings with flow control	[36, 54]

IV CONCLUDING REMARKS

This review indicates that the degradation of engineering materials used in erosive environments is a complex problem that depends on several factors, including material properties, microstructure, surface morphology and erosion condition. Surface modifications, such as hardfacing, thermal spray coatings, friction stir processing and advanced multilayer coatings, can greatly improve erosion resistance when tailored to optimum conditions of application. The studies reviewed show that resistance to erosion is not determined only by the surface hardness. Still, it also depends on other parameters, such as the arrangement of phases, the architecture of coatings, and resistance to crack propagation, along with toughness. Hybrid methods of surface engineering, such as coating deposition combined with post-processing treatments, are a promising approach to overcoming the barriers inherent to each method in isolation. In the next stage, studies should be conducted to correlate experimental tests with numerical simulations to develop a robust set of guidelines based on erosion test conditions.

Acknowledgements

The authors express deep gratitude to I. K. Gujral Punjab Technical University, Jalandhar (Punjab), India for allowing them to carry out this research work.

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