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Solid Particle Erosion Behavior of Inconel Coatings at Elevated Temperatures: A Review

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Abstract - High-temperature solid particle erosion is a critical degradation mechanism affecting mechanical components in power plants, boilers, turbines, and automotive systems operating within the temperature range of 400–1200 °C. Boiler tube steels such as ASTM SA213 T11, T22, T-91, and GrA1 are particularly vulnerable due to continuous impingement of silica-rich fly ash particles and other hard phases. This review paper critically examines recent research on the application of Inconel-based thermal spray composite coatings to enhance the erosion resistance of boiler tube materials. Emphasis is placed on coating deposition techniques such as High Velocity Oxy-Fuel (HVOF) and Cold Spray processes, utilizing Inconel 718 and Inconel 738 as matrix materials reinforced with alumina (Al_2O_3) particles in varying proportions (10–30 wt%). The influence of reinforcement content on microstructural characteristics, including microhardness, porosity, surface roughness, density, and erosion performance at different impact angles (30° and 90°), is systematically analyzed. The reviewed studies consistently report that increasing Al_2O_3 content improves coating hardness, reduces porosity, and significantly decreases volumetric erosion loss compared to uncoated steels. Overall, the literature confirms that Inconel-based composite coatings deposited via advanced thermal spray techniques are highly effective in extending the service life of boiler components operating under aggressive high-temperature erosive environments.

Keywords: - Solid particle erosion; Thermal spray coatings; Nanoparticle reinforcement; Erosion resistance; Nanocomposite coatings; Surface engineering; Microstructure–property relationship

1. INTRODUCTION:

The various mechanical components employed in power generation plants, automotive systems, machine tools, and furnaces were subjected to severe high-temperature solid particle erosion during service. The surface deterioration of these components occurred within an elevated temperature range of 400–1200 °C, leading to significant material degradation under harsh operating conditions [1]. The solid particles, including combustion by-products present in exhaust gases within engine manifolds and turbocharger casings, as well as fly ash in boilers, interacted with the component surfaces at different velocities, causing progressive surface damage under operational conditions [2]. The extended exposure to such severe operating conditions often resulted in structural degradation and eventual bulk failure of components. Continuous interaction with high-temperature erosive particles weakened the material integrity, promoted crack initiation and propagation, and accelerated material loss. Consequently, the overall durability and reliability of the components were significantly reduced, leading to a substantial decline in their service life [3, 4]. High-temperature erosion resulting from the impact of solid particles entrained in a fluid stream was recognized as a critical issue in many engineering systems involving fluid–surface interaction. The continuous bombardment of these particles at elevated temperatures led to progressive material degradation and surface damage. In coal-fired power plants, high-temperature solid particle erosion played a major role in the deterioration and premature failure of key components such as steam turbines and gas turbines, thereby reducing their operational efficiency and service life [5], boiler tubes [6]. In several instances, these failures led to unexpected plant shutdowns. The damage primarily occurred due to intense erosion caused by unburnt carbon particles and various oxides present in the fly ash, which continuously impinged on the component surfaces under high-temperature conditions [7]. Since the bonding mechanism between the sprayed particles and the substrate required significant plastic deformation, it was essential for the particle velocity to exceed a specific minimum limit, known as the critical impact velocity[8-10].It was generally considered that the most damaging constituents in fly ash were quartz, a crystalline form of SiO_2, and mullite. More than one-quarter of boiler tube failures worldwide were attributed to erosion caused by fly ash [11, 12].Whenever a particle struck the surface, it removed a minute fragment of material through a cutting action. Although the material loss caused by a single particle was negligible, the cumulative effect of numerous particles impacting over an extended duration resulted in substantial material

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degradation and severe erosion. Erosive wear was therefore anticipated in such environments and represented a critical concern in many engineering applications, including aircraft engines, steam turbines, jet turbines, and boiler tubes [13, 14]. The solid particle erosion behavior of a component surface was influenced by the characteristics of the base metal or by the combined properties of the base metal and the applied coating. It was also governed by several critical parameters, including operating temperature, angle of impact, particle velocity, and the properties of the erodent such as its composition, size, and shape[15]. The turbine components were exposed to various surface degradation mechanisms such as hot corrosion, erosion, and related damage processes. Industries including mining, automotive, and aerospace extensively utilized thermal spray coatings to protect critical components operating under severe service conditions. Among the different thermal spray techniques available, the High Velocity Oxy-Fuel (HVOF) process was widely adopted due to the significant advantages it offered, such as reduced porosity, enhanced bond strength, and superior hardness of the deposited coatings [16]. One of the most effective approaches for extending the service life of engineering components was the application of thermal spray coatings composed of superalloys, which exhibited outstanding resistance to erosion and corrosion [6, 17-19]. Consequently, the demand for advanced surface protection technologies increased significantly within the power generation industry. Thermal spray coatings demonstrated effective performance and widespread applicability in high-temperature operating environments[17-19]. The coating industry's primary objective was to develop dense coatings from metallic and ceramic powders that exhibited strong adhesion to the substrate along with minimal porosity. These coatings provided enhanced mechanical strength and formed a protective surface layer capable of resisting wear, erosion, and corrosion, thereby making them an ideal solution for various industrial applications[20]. Coatings provided an effective means of extending the operational limits of materials at the upper range of their performance capabilities. They enabled the retention of the substrate's mechanical properties while simultaneously offering protection against wear and high-temperature corrosion[21].Coatings could be deposited through various techniques such as thermal spraying (including flame spraying, vacuum plasma spraying, low-pressure plasma spraying, and High Velocity Oxy-Fuel spraying), as well as by sputtering or evaporation methods. However, thermal spray coatings were generally preferred for industrial applications due to their versatility, cost-effectiveness, and suitability for large-scale components[22, 23]. Thermal spraying had emerged as a significant and increasingly advanced technique in the field of surface engineering. A wide range of coating properties, including enhanced wear resistance, improved hot corrosion resistance, and effective thermal or electrical insulation, were achieved through the selection of appropriate coating materials and deposition techniques [24].

2. LITERATURE REVIEWS

This section presents a summary of the studies conducted by various researchers on managing wear and erosion in different boiler steels through thermal spray coatings. The problem formulation is defined based on a thorough evaluation of the literature, which will be detailed in the subsequent section.

Vasudev et al [2022] studied the effect of different composition of aluminum oxide Al_2O_3 coating on Inconal-716 matrix affect their erosion resistance, hardness, and surface roughness at 800ºC temperature. High velocity oxy-fuel (HVOF) was used for coating of Al_2O_3 on substrate. Result of hardness enhances in coated substrate as compare to uncoated substrate and surface roughness and porosity also improved in coating substrate. The INAL2 (Inconal+20 wt% Al_2O_3) found highest fracture toughness. The brittle failure was occur in uncoated base material and coated INAL3 (Inconal+30 wt% Al_2O_3) at 90º impact angle and ductile failure found in INAL1 (Inconal+10 wt% Al_2O_3) and INAL2 at 30º impact angle[25].

Padmini et al [2021] investigated the application of cold-sprayed Ni-based coatings on boiler tubes and turbine blades to enhance the erosion resistance of the (T11) substrate. The coated material exhibits high erosion resistance due to its dense morphological structure, minimal oxide phases and increased hardness compared to the uncoated substrate. The solid particle erosion resistance of the IN 738 coating is three times higher than that of T11 steel at a 30° impact angle and two times higher at a 90° impact angle at elevated temperatures. The formation of grooves, platelet formation, ploughing and plowing marks at a 30° impact angle indicates ductile wear, whereas craters formed at a 90° impact angle suggest brittle wear[26].

Prashar and Vasudev [2024] focused on the application of Inconel 625 + 30% Al_2O_3 (IN30AL) blended powders onto commercially used ASTM SA210 GrA1 boiler steel, utilizing the high-velocity oxy-fuel (HVOF) spraying technique. The crack-free coating surface thickness was found to be in the range of 200 µm to 250 µm. The porosity of the surface formed through high-velocity oxy-fuel (HVOF) spraying was approximately 2%.. This is likely due to the partial melting of Al_2O_3-reinforced particles when exposed to the high temperatures of the HVOF flame. In contrast, the porosity of heat-treated IN30AL coatings is reported to be around 1%.The coated substrate exhibited brittle erosion behavior at both 30-degree and 90-degree impact angles, while the uncoated substrate demonstrated ductile erosion behavior at the same angles[27].

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3. MATERIAL OF SUBSTRATE

The cast iron (CI) has been extensively employed in the fabrication of furnace components, machine tool structures, turbocharger housings, and exhaust manifolds due to its excellent castability, wear resistance, and mechanical stability [28]. These components were required to endure severe erosive wear under elevated temperature conditions ranging from 300 °C to 1000 °C [29]. Cast iron alone was unable to provide adequate erosion resistance to such components at elevated temperatures. Therefore, the surfaces of the cast iron components required appropriate modifications to improve their resistance to erosive degradation under high-temperature conditions[25]. Table 1

Table 1:								
Chemical Composition of ASTM SA213 T11 Steel (% by weight)								
Grade	**C**	**Mn**	**Si**	**P**	**S**	**Cr**	**Mo**	**Fe**
T11	0.14	0.41	0.016	0.42	0.02	0.99	0.82	Balance

The erosion behavior of steels employed in reheater and superheater tubes, such as ASTM SA213 T11 coated with Inconel, has been scarcely reported in the existing literature. Therefore, the present study aimed to develop Inconel 738 coatings on boiler steels in order to enhance their high-temperature erosion resistance and provide a comprehensive understanding of their performance under severe operating conditions[26]. T-91 boiler tube steel was selected as the substrate material for the present investigation. The substrate used in this study was supplied by Guru Nanak Dev Thermal Power Plant, Bathinda, Punjab (India), and is commonly utilized in the fabrication of boiler tubes. This material is extensively employed in steam boiler applications across various sectors, including the chemical industry, power generation plants, fertilizer units, and paper mills, owing to its excellent high-temperature strength and creep resistance [30]. Fe-based T22 steel, which is commonly employed as a boiler tube material in several coal-fired thermal power plants in the northern region of India, was utilized as the substrate material for the present study[31].GrA1 boiler steel obtained from Raichur Thermal Power Plant was selected as the substrate material for the present investigation. The material was machined and prepared to the required dimensions of 75 × 25 × 5 mm for the Cold Spray process. The chemical composition of the substrate material is presented in Table.2 [32].

Table 2:								
Nominal Composition of the Test Steel Specimen.								
Substrate	ASTM code	C	Mn	Si	P	S	Cr	Fe
GrA1	ASTM SA210	0.2	0.93	0.5-1.0	0.025	0.035	0.055	Bal

4. COATING MATERIAL

Inconel 718 has been extensively utilized in rocket components and jet engine applications due to its exceptional performance under extreme service conditions. It has exhibited superior mechanical strength along with excellent creep resistance at elevated temperatures, making it highly suitable for high-temperature structural applications [33]. The application of Inconel in aero-engines, turbine blades, and boiler tubes of thermal power plants has gained considerable significance owing to its excellent resistance to high-temperature erosion–corrosion. Its superior thermal stability and structural integrity at elevated temperatures have made it a preferred material for components operating under severe service conditions [34] and aggressive operating conditions [35]. A commercially produced IN 738 powder, procured from Plasma Giken Co., Ltd., Japan, was employed as the feedstock material for coating deposition through the Cold Spray process [26]. Table 3. Presents the chemical composition, size, shape and manufacturing method of the powder [26].

Table 3 :								
Chemical Composition and Other Details of IN 738 Powder								
Chemical Composition (wt%)						**Powder Particle Size**	**Shape**	**Manufacturing Method**
Cr	**Co**	**Ti**	**Al**	**W**	**Ni**			
16	8.5	3.5	3.5	2.5	Balance	05 – 25 µm	Spherical	Gas atomised

The deposition of Inconel 738 coatings on T11 boiler steel was attempted for the first time in this study and was successfully accomplished using helium as the propellant gas [26]. A commercially available 80% Cr_3C_2–20% (Ni–20Cr) coating powder (agglomerated and sintered grade, Amperit 586.054, supplied by H.C. Starck GmbH, Germany) was utilized for the development of the coating [30]. The 70Ni–30Cr and 50Ni–50Cr coatings were deposited using an indigenously developed Cold Spray system. The coating thickness achieved on the substrate was approximately 100 µm. The coated specimens were subsequently sectioned by wire-cut EDM to dimensions of 25 × 25 × 5 mm. During deposition, the stand-off distance between the nozzle exit and the substrate surface was maintained at 40 mm, and the transverse gun traverse speed was controlled at 32 mm/s. The processing parameters adopted for the Cold Spray coating are summarized in Table 4 [32].

Table 4-: Parameters of Cold Spray Process

Parameters	Specifications
Gun Pressure	12 bar
Temperature	400
Carrier Gas	Compressed Air
Gas Flow Rate	1.96 m3/min
Heat Power Source	30 kW
Coating Thickness	100

5. REINFORCEMENT MATERIAL

Alumina (Al_2O_3) was selected as the reinforcement material owing to its low cost, chemical inertness, high hardness, and excellent thermal stability, even at elevated temperatures [25]. The improvement of erosion resistance at elevated temperatures has been a critical concern in boiler tube applications. The incorporation of Inconel 718 into pure nickel powder has been reported to significantly enhance the erosion resistance of cold-sprayed Ni-based coatings [36].

6. RESULT AND DISCUSSION:

The results obtained from the previous research study are summarized and presented in a table 5.

Sr No	**Referencs**	**Material of Substrate and Coating**	**Results**

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1	Vasudev et al [2022]	Cast iron and Inconel718 + 10 wt%Al2O3, Inconel718 + 20 wt%Al2O3 and Inconel718 +30 wt%Al2O3	The results showed that increasing Al_2O_3 content enhanced the microhardness and improved erosion resistance at 800 °C. Additionally, surface roughness and porosity decreased with higher alumina incorporation, indicating improved coating quality.
2	Padmini et al [2021]	ASTM SA213 T11 steel and Inconel 738	The IN 738 coating exhibited significantly superior high-temperature erosion resistance compared to T11 steel, being approximately three times more resistant at 30° and nearly two times at 90° impact angles.
3	Prashar and Vasudev [2024]	ASTM SA210 GrA1 and Inconel625+30%Al2O3 (IN30AL)	HVOF-sprayed coatings exhibited low porosity of approximately 2%, primarily due to the partial melting of Al_2O_3 reinforcement particles in the high-temperature flame, which enhanced coating densification. Furthermore, heat-treated IN30Al coatings showed an even lower porosity of about 1%, attributed to diffusion-driven crack healing and pore filling during heat treatment.

7. CONCLUSION

- This study demonstrated that thermal spray coatings based on Inconel superalloys significantly enhanced the high-temperature solid particle erosion resistance of boiler tube steels. The incorporation of alumina reinforcement within the Inconel matrix resulted in increased hardness and reduced porosity, thereby contributing to improved erosion performance at elevated temperatures.
- The erosion behavior was strongly influenced by the impact angle, coating composition, and substrate characteristics. The coated specimens exhibited substantially lower volumetric erosion loss compared to the uncoated steels, particularly at elevated temperatures around 800 °C. Among the developed coatings, Inconel 738 showed superior erosion resistance at both 30° and 90° impingement angles. The findings confirmed that composite coatings fabricated through HVOF and Cold Spray techniques provided an effective surface engineering strategy for protecting boiler tubes and turbine components against severe erosive wear.
- Overall, the application of Inconel-based composite coatings proved to be a reliable and industrially viable approach for enhancing component durability, minimizing maintenance costs, and improving operational efficiency in thermal power plants and other high-temperature engineering systems.

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