Erosion studies of plasma sprayed WC-12%Co, Cr₃C₂-25%NiCr, 80%Ni-20%Cr, 87%Al₂O₃-13%TiO₂ coatings on ASTM A36 steel

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Abstract
WC-12%Co, Cr₃C₂-25%NiCr, 80%Ni-20%Cr, 87%Al₂O₃-13%TiO₂ coatings were deposited by Air Plasma Spray (APS) technique on ASTM A36 steel. Erosion behaviour of sprayed coated samples were investigated at three different impact angles (45°, 60° and 90°). The mechanism of erosion was investigated on uncoated and coated samples. The rate of erosion of the substrate first increased with increasing angle of impact and then gradually decreased. But the erosion rate of the coated samples increased steadily. Substrate shows the higher metal removal whereas coating shows the higher erosion resistance. WC-12%Co coated samples performed well in erosion testing and offered best erosion resistance as compared to the substrate and all other coatings. Ductile fracture takes place on substrate material at higher impact angle. Overall, all the coated samples have shown less erosion propensity when compared to the bare one.

1. Introduction
Induced draft (ID) fans are the key parts of coal fired power plants, the blades are usually of ASTM A36 steel substrate which have excellent mechanical properties. However, at elevated temperatures solid particle erosion of blades takes place due to high pressure air flow. Thus, by enhancing the erosion properties of blades, its surface life can be extended. For providing the protective measures on blade surface, coating by plasma spraying method is an efficient and economic technique [1–5].

It is well known that cermet coatings have high hardness. In industries among all the cermet coatings, tungsten carbides, nickel, chromium and titanium based coatings are widely utilised for their high erosive-corrosive wear resistance [6–9]. A huge number of research studies have been conducted by the researchers by utilising the tungsten based and nickel based coatings to enhance the erosive wear properties [10–13]. Thus, it can also be utilised for coating of ID fan blades in severe corrosive conditions [14–17]. Many researchers believed different factors of coating like hardness, bond strength, toughness, different hard phases and binders have effect on erosion behaviour [18, 19]. Increasing the hardness will result in erosion resistance and improved surface properties [20, 21]. Lee [22], Arabi et al [23] and Zamani et al [24] concluded in their findings that the erosion resistance material must have continuous and hard matrix with consistent distribution of hard elements in its structure. This has become the spotlight for present study.

Plasma spraying process is widely utilised in industry for its special key feature of stable stream consisting of molten particles moving with high velocity which deposit the coatings efficiently [25]. However, plasma spray coating deposited structure tends to have micro cracks, porosity and lamellar structure [26, 27].

In this paper, the cermet coatings like tungsten carbides, nickel, chromium and titanium-based coating were deposited on ASTM A36 steel substrate via plasma spray coating technique. The effect of erosion resistance of all coatings was examined by air jet erosion tester. Erosion behaviour at different impact angles was investigated through morphologies. This will help in providing the characteristics and performance of coatings to improve the service life of I.D. fans in coal fired thermal power plants.

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Figure 1. SEM/EDAX of coating powders; (a) Cr₂C₃-25%NiCr powder, (b) WC-12%Co powder, (c) Ni-20%Cr powder and (d) Al₂O₃-13%TiO₂ powder.
2. Experiment

2.1. Material preparation procedure

In present analysis, WC-12%Co, Cr₃C₂-25%NiCr, 80%Ni-20%Cr, 87%Al₂O₃-13%TiO₂ coating powders are utilised for surface coating on ASTM A36 steel (sample size: 25 mm × 25 mm × 5 mm). The compositions and their particle size of powders used as coating are listed in table 1. Figure 1 shows the SEM/EDAX morphologies of all powders used for coating on substrate material. The average coating powder particle size was nearly 5–45 μm. Before spraying the coating on substrate, the samples were pre-treated by polishing (grit paper utilised are P220, P400, P600, P800 and P1000 followed with 1/0 and 2/0 grades polishing papers), degreasing and grit blasting (the mentioned grit blasting process creates the surface roughness of about 9–12 μm Ra which was enough for the adhesion of the surface coatings). The coatings were developed at ‘Metallizing Equipment Co. Pvt. Ltd Jodhpur’ using Air Plasma Spray Technique (MPS).
The process parameters were optimized after conducting several trials as the morphology of the different coating powders selected was different. Table 2 shows the optimized parameters used for Air Plasma Spray coating technique. Coating powders morphology was obtained with SEM along with EDAX as revealed in figure 1.

Figure 3. SEM/EDAX morphology ASTM A36 steel coated with (a) Cr$_3$C$_2$-25%NiCr, (b) WC-12%Co, (c) Ni-20%Cr, and (d) Al$_2$O$_3$-13%TiO$_2$ coating.
2.2. Characterization of coated specimens

For the coated specimen, surface roughness (Ra) was measured with surface roughness tester (Mitutoyo SJ-201, Japan). Five measurements were taken at different locations and each value was reported with center line average method. The metal spray coating process is intermittent; therefore, some pores and voids tend to appear. In order to identify the porosity, images were captured by the PMP3 inverted metallurgical microscope. The

Figure 4. SEM back scattered micrograph for coating thickness of (a) Cr₃C₂-25%NiCr coating, (b) WC-12%Co coating, (c) Ni-20%Cr coating and (d) Al₂O₃-13%TiO₂ coating.

Table 2. Air plasma spray technique parameters.

| Parameter                        | Specification                  |
|----------------------------------|-------------------------------|
| Working gases                    | Hydrogen and nitrogen         |
| Fuel gas                         | Hydrogen                      |
| Carrier gas                      | Nitrogen                      |
| Pressure of fuel gas (Hydrogen)  | 8 bar                         |
| Pressure of carrier gas (Nitrogen)| 8 bar                         |
| Consumption of working gases     |                               |
| Hydrogen                         | 5.5 ml min⁻¹                  |
| Nitrogen                         | 40.1 ml min⁻¹                 |
| Water consumption rate           | 15–25 l/min                   |
| Diameter of barrel               | 6 mm                          |
| Coating thickness                | 200 μm                        |
| Coating capacity at the rate     | 2–10 Kg h⁻¹                   |
| System control                   | Manual/Semi auto              |
| Power supply from mains          |                               |
| Current                          | 506 Amp                       |
| Voltage                          | 63.7 V DC                     |
| Power                            | 32.1 kW                       |
magnification was selected in such a way that it allows the resolution of voids that provides the total percentage of porosity. Stereographic images were used systematically to identify the voids in the form of light gray contrast spots. The micro-hardness of the coatings was measured using micro 'Vicker hardness tester with model number: MVK-H2, Akashi, Japan'. Pull-off test was conducted as per ASTM C-633-2013 standards to measure the bond strength of coating at 'Metallizing Equipment Co. Pvt. Ltd Jodhpur'. In this test, coating is applied to the substrate fixture which is in the form of a cylinder. This coating substrate fixture is then glued with commercially available epoxy resin adhesive (a nominal strength about 70 MPa) provided by ‘Metallizing Equipment Co. Pvt. Ltd Jodhpur’ to another cylinder with same diameter. The resulting assembly was subjected to a normal force. Three test pieces were used for each type of coating and then calculated average value was taken as bond strength.

Table 3. Parameters for air jet erosion testing.

| Erodent material  | Alumina (Al₂O₃) |
|-------------------|-----------------|
| Size of erodent   | 50 μm           |
| Erodent Velocity  | 30 m s⁻¹        |
| Flow rate of erodent | 2 gm min⁻¹    |
| Impingement angle | 45°, 60° and 90° |
| Nozzle diameter   | 1.5 mm          |
| Test time         | 30 min          |
| Test temperature  | 150 °C–Sample temperature |
|                   | 180 °C–Air temperature |

Figure 5. Macro images of coated and uncoated samples after erosion test.
2.3. Erosion testing with solid particles

To understand the solid particle erosion mechanism of the coatings, erosion studies of the bare as well as coated ASTM A36 steel were carried out using air jet erosion tester (TR-471-M10). The tests were conducted with certain set of conditions, the details are presented in table 3. The test rig comprised of pneumatic and electrical control box with compressor used for impact of erodent with velocity on specimen, mixing chamber for erodent uses motor through the timing belt, erodent feeding system which allows the erodent particles to move down due to gravity via throat and erodent collection chamber, furnace unit raise the temperature of chamber (room temperature to 1000°C), nozzle which conveys the stream of gas that contains the erodent particle, and specimen holder with different impact angles (45°, 60° and 90°) as shown in figure 2.

2.4. Measurement of rate of erosion

A non-contact type optical profilometer was used to measure the volume loss of material due to air jet erosion testing. This approach was utilized to evaluate surface properties, like: surface and depth topography along with erosion volume loss. ‘Veeco Wyko NT 1100 Optical Profiling System’ (Profilometer) of ‘Ducom, Bangalore (India)’ was utilized for measuring the mean erosive depth with a Veeco. This equipment characterizes and measures the volume of the scars caused by erosion wear and topographical features with a remarkable precision and accuracy. The digitized data acquired from a 3D interferogram is used to create a map of the surface at six different locations. The uneroded part of the tested specimen was used as a reference plane in order to find the depth of erosion (for calculating volumetric loss) on scar produced by impact of the erodent. The scar area of eroded surface was measured by utilizing the stereo microscope embedded with image analysis software -VUE-2014.

3. Results

3.1. Characterization of coatings

SEM/EDAX analysis of sprayed coated samples is illustrated in figure 3. The SEM images show the clear structure with some voids and pores between lamellas. EDS analysis shows the elemental composition of each sprayed coating with which coating powders and coating can be validated. It was indicated from the elemental composition that the inter diffusion of alloying elements occurred at the interface of substrate and coating from the cross-section SEM morphologies as shown in figure 4. It also shows the coating thickness, epoxy, and substrate.
Table 4 shows the porosity, bond strength, microhardness and surface roughness of the sprayed coatings. The surface roughness of WC-12%Co coated sample has the lesser surface roughness i.e. 2.52–4.28 μm and rest other three coating have almost same roughness of 4–7 μm. In that order, the porosity of the coated samples is very less in each coating which was less than 1%. The micro-hardness of coated samples reached to 1076Hv in WC-12%Co coating and rest all coatings have almost 700Hv. These measurements are in confirmation with the results of Heydarzadeh and Ghadami [28].

3.2. Solid particle erosion behavior
Erosion behaviour of any material is phenomena of removal of complex material from the surface which is namely solid particle erosion. The objective of this analysis is to identify and attempt to characterize response of coatings to solid particle erosion. Figure 5 shows the effect of erodent on the substrate and coated samples at...
three different impingement angles. During this investigation it was observed that the scars formed on the specimens due to continual strike of erodent material at different angle were of different shape. Elliptical shape was formed when the impingement angle was $45^\circ$ and $60^\circ$, whereas circular scar was formed when the angle of impingement was $90^\circ$. The dark gray coloured ring can be visualised after the examination of specimens. It was also noticed that the area which was uneroded was having rough surface as compared to the eroded area. The comparison of volume ($\text{mm}^3/\text{g}$) erosion rate of bare sample with four different plasma coating materials Cr$_3$C$_2$-25%NiCr coating, WC-12%Co coating, Ni-20%Cr coating and Al$_2$O$_3$-13%TiO$_2$ coating eroded at three different impingement angle i.e., $45^\circ$, $60^\circ$ and $90^\circ$ are displayed in figure 6.

It can be observed that for uncoated ASTM A36 steel and Ni-20%Cr coated specimens, the volume erosion rates were highest at $45^\circ$ angle of impingement and started reducing when increased to $60^\circ$ and became minimum at $90^\circ$. The findings are in agreement with results available in literature [29–32]. On the other hand, for substrate coated with WC-12%Co showed a minimum volumetric erosion rate at $45^\circ$ angle of impingement, highest at $60^\circ$ and an intermediary value for $90^\circ$. This is nearer to the behaviour of ductile materials and is agreement with findings of Mruthunjaya and Parashivamurthy [33]. The substrates coated with WC-12%Co possess a advantageous combination of toughness and hardness due to remarkable WC hardness and binder phase (Co) toughness. Hardness has a considerable effect on erosion of materials through the modes of plastic deformation, although fracture toughness is a controlling factor in solid particle erosion comprising a brittle fracture. According to Hussainova et al [34] it is apparent that hardness alone is

| Coating powder                  | Roughness (Ra) | Porosity in % | Microhardness | Bond strength |
|--------------------------------|----------------|---------------|---------------|--------------|
| Cr$_3$C$_2$-25%NiCr            | 4.08–4.78 $\mu$m | 0.49          | 682–709 Hv    | 67.19 MPa    |
| WC-12%Co                       | 2.52–4.28 $\mu$m | 0.23          | 997–1076 Hv   | 53.34 MPa    |
| Ni-20%Cr                       | 4.77–6.98 $\mu$m | 0.89          | 660–670 Hv    | 69.15 MPa    |
| Al$_2$O$_3$-13%TiO$_2$         | 2.94–3.76 $\mu$m | 0.82          | 682–703 Hv    | Pa           |

Figure 7. (Continued.)

Table 4. Surface roughness, microhardness, porosity and bond strength values of plasma spray coatings on ASTM A36 steel.
not the best guide to evaluate the erosion behaviour of WC-Co coatings but it also depends on the mechanisms of material removal, toughness and the microstructure [20]. The substrate coated with Cr3C2-25%NiCr showed highest volumetric erosion at 90° angle of impingement, with reduction at 60° and became minimum 45° in agreement with findings of Vicenzi [35] and Hawthorne et al [36]. Likewise, Al2O3-13%TiO2 coated substrate showed the similar behaviour of brittle materials in accordance with the results reported by Wang et al [37] and Matikainen et al [38].

Therefore, at impingement angles of 45°.

WC-12%Co coating performed best among its counterparts, whereas Ni-20%Cr Coating has shown higher erosion rate as compared to bare sample, Cr3C2-25%NiCr and Al2O3-13%TiO2 coatings have shown lesser erosion rates than bare sample but more than WC-12%Co Coating.

Moreover, at impingement angles of 60° and 90°.

WC-12%Co coating performed best among its counterparts, whereas Ni-20%Cr and Al2O3-13%TiO2 coatings have shown the higher erosion rates compared to bare sample, Cr3C2-25%NiCr coating has shown less erosion rate than bare sample but more than WC-12%Co Coating.

3.3. Solid particles erosion mechanism

To detect the erosion mechanism, surfaces of eroded bare and coated samples were anlaysed by SEM/EDAX.

SEM micrographs at an angle of 45° of bare specimen and coated specimens shown in figure 7 indicates the erodent material presence and removal of material, the formation of lip and craters with small cracks on bare specimen and Ni-20%Cr coated specimen. It can be deduced that the cutting and ploughing played the dominant role in erosion of materials which is characteristics wear behavior of ductile materials [39]. SEM micrographs at an angle of 60° of bare specimen and coated specimens shown in figure 8 indicates erodent material presence and removal of material, the formation of lip and craters with small cracks in bare specimen and Ni-20%Cr coated specimen. Moreover, the brittle fractures were observed in Al2O3-13%TiO2 coated specimens in comparison with the bare specimen. Therefore, it can be understood that the Cr3C2-25%NiCr and WC-12%Co both cermet coatings were still protecting the base material after the test was conducted.
The volumetric erosion of the Cr3C2-25%NiCr and Al2O3-13%TiO2 coated substrate pointed out that highest erosion took place at angle of impingement of impact angle of 90° indicating brittle behaviour of coating in accordance with the results of Guilemany et al [40]. Since these coatings are hard as well as brittle by nature, therefore brittle erosive behaviour is identified. The authors reported that in brittle materials, material loss on account of solid particle erosion takes place mostly by the creation and interaction of a subsurface micro crack network. Moreover, the authors suggested that in such type of materials, the removal of material is related to the creation and propagation of cracks. The cracks develop on the surface when the surface stresses attain a critical value to start micro cracking. Meanwhile, these cracks spread and intersect with the surface, the material is eroded. Thus, in brittle materials the erosive wear resistance is a function of its resistance to formation and propagation of cracks. In the present study, substrate material coated with Cr3C2-25%NiCr and Al2O3-13%TiO2 powders have shown brittle erosion behaviour due to cracking and chipping of the surface. On account of continual impingement of erodent material (alumina) the radial and lateral...
cracks were evolved and subsequently fractured and loosened pieces were eliminated. Ultimately numerous minor voids and pits were created. The volumetric erosion was higher at an impingement angle of 90°, moderate at an 60° and lowest 45°. The variation in volume erosive wear rates for oblique and normal impingement angles may be associated with the diverse material elimination modes in these two situations. At an impact angle of 45°, the micrographs as shown in figure 7 revealed the deformity on the surface resulting in the formation of craters, cracks, brittle fracture and chipping. At 90° again, the micrographs (shown in figure 9) revealed the deformation at the surface resulting in the formation of craters, cracks, brittle fracture, fractured splat and splat debonding at the upper surface layer of the coating material. At a higher angle of impingement, the kinetic energy of the striking erodent material contributes considerably to consecutive impact. The brittle nature of materials allows the cracks to propagate quickly. The subsequent impacts will easily remove the surface material through the elimination of the upper layer of coating material. Accordingly, the volumetric erosion was high at an impact angle of 90°.

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**Figure 9.** SEM/EDAX of eroded samples at 90° impact angle: (a) bare ASTM A36 steel, (b) Cr3C2-25%NiCr, (c) WC-12%Co, (d) Ni-20%Cr and (e) Al2O3-13%TiO2.
4. Conclusions

- Microhardness of plasma sprayed Cr$_3$C$_2$-25%NiCr, WC-12%Co, 80%Ni-20%Cr, 87%Al$_2$O$_3$-13%TiO$_2$ coatings was 682–709 Hv, 997–1076 Hv, 660–670 and 682–703 Hv. It signifies the higher the hardness higher the erosion resistance.

- The porosity of each coating was less than 1% which represents that the coating powder deposition on substrate is almost homogenous and powder particles are melted vibrantly through plasma gun.

- Volume erosion rate of Cr$_3$C$_2$-25%NiCr, WC-12%Co coated specimens have better erosion resistance property than 80%Ni-20%Cr, 87%Al$_2$O$_3$-13%TiO$_2$ coatings at 45°, 60° and 90° impact angle and protected the base material from erosion.

- Volume erosion rate of Cr$_3$C$_2$-25%NiCr, WC-12%Co coated specimens have better erosion resistance property than 80%Ni-20%Cr, 87%Al$_2$O$_3$-13%TiO$_2$ coatings at 45°, 60° and 90° impact angle and protected the base material from erosion.

- 80%Ni-20%Cr coating has higher erosion volume rate as compared to ASTM A36 steel at 45°, 60° and 90° impact angle. Therefore unable to protect the base material from erosion.

- 87%Al$_2$O$_3$-13%TiO$_2$ coating has lesser erosion volume rate at 45° and gradually increases at 60° and maximum at 90°. On the other hand, substrate material shows the opposite behaviour as of 87%Al$_2$O$_3$-13%TiO$_2$ coating.

- Erosion behaviour at impingement angles of 45°: WC-12%Co Coating performed best among the counterparts, whereas Ni-20%Cr Coating shown the high erosion rate than bare sample, Cr$_3$C$_2$-25%NiCr Coating and Al$_2$O$_3$-13%TiO$_2$ Coating shown less erosion rate than bare sample but more than WC-12%Co Coating.

- Erosion behaviour at impingement angles of 60° and 90°: WC-12%Co Coating performed best among the counterparts, whereas Ni-20%Cr Coating and Al$_2$O$_3$-13%TiO$_2$ Coating shown the high erosion rate than
bare sample, Cr$_3$C$_2$-25%NiCr Coating shown less erosion rate than bare sample but more than WC-12%Co Coating.

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