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Surface erosion behaviour over NiCrBSi-Al$_2$O$_3$ composite coatings

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Abstract

For hydro turbine components High Velocity Oxy Fuel (HVOF) thermal spraying process was adopted for three different types of coatings i.e. NiCrBSi-5%Al$_2$O$_3$ (N5A), NiCrBSi-10%Al$_2$O$_3$ (N10A) and NiCrBSi-15%Al$_2$O$_3$ (N15A) on Grade 420 Stainless steel, the coatings being characterized by Scanning Electron Microscope (SEM), x-ray Diffraction (XRD) and optical microscope. With measurements of surface roughness, thickness, micro hardness and porosity of the coatings, the erosion tests were conducted in a slurry-jet erosion tester at 30°, 60° and 90° impingement angles, jet velocity of 20 m s$^{-1}$ and erodent size of 200 µm. The optical microscopy images of the coated samples exhibited lamella structure of the coatings. The N15A coating exhibits highest micro hardness value of 715 ± 31 HV$_{0.3}$ followed by N10A (557 ± 22 HV$_{0.3}$) and N5A (407 ± 15 HV$_{0.3}$). The grade 420ss shows the lowest micro hardness value (272 ± 5 HV$_{0.3}$). The surface morphology of the eroded samples was studied using SEM. The mechanisms involved in erosion of all the coated surfaces are removal of splats, lip formation, ploughing action and micro cutting whereas of bare steel, ploughing action, micro cutting and lip formation along with appearance of pores and craters. It was found that amongst the three coatings NiCrBSi-15%Al$_2$O$_3$ exhibited the lowest erosion and all the coatings offered better wear resistance than the uncoated steel.

1. Introduction

Silt erosion has become a serious problem in hydro power plants affecting its performance and efficiency and sometimes leading to the shutdown of the hydro power plants in the worst case. The silt erosion is quite relevant with the small hydro power plant present in the northern part of our country especially with those hydro power plants which run from the water flowing from the Himalayan ranges [1–4]. The selection of hydro turbine material is an important factor for decreasing the rate of silt erosion. Even though proper material is chosen for hydro turbine parts, the material parts get damaged in due course of time. To decelerate the rate of damage a coating is provided on the turbine material. Many researchers have designed and conducted experiments to study the behaviour of different coating materials [5–10].

The various coating processes include vapour deposition, chemical and electrochemical technique, thermal spraying, roll-to-roll and physical coating. High velocity oxy fuel coating is one of the thermal spraying techniques of coating the material. In HVOF coating procedure, the deposition takes place at a higher deposition velocity, higher impact energy and lower deposition temperature resulting in the coating properties like low porosity, high hardness, high yield stress, enhancement of adhesiveness to substrate and reduction of compressive residual stresses. The HVOF procedure is less expensive, highly flexible and the thickness of about few microns of the coating material can be deposited by this procedure. But the disadvantage of this process is coating of the internal surfaces [11, 12]. Powder sizes ranging from 4 to 45 microns are used for coating and the coating thickness of 100 microns to 12 mm can be obtained by this procedure. NiCrBSi coating is abrasive wear and corrosion resistant. It is less hard in comparison to ceramics and carbides. So NiCrBSi mixed with a suitable ceramic will satisfy the purpose of a hard, wear resistance and corrosion resistance coating. Alumina is the most eminent ceramic material with excellent chemical and physical stability. It has wide applications because of its
high hardness, high strength and high wear resistance. Grade 420ss is a high carbon steel with minimum chromium content of 12%. It offers good ductility in its annealed state and excellent corrosion and erosion resistance properties when the metal is polished, surface grounded or hardened.

Studies from the literature revealed that HVOF thermal spraying process has been widely used by many investigators to coat the substrate for protection against erosion [13–20]. Praveen et al [21] studied the effect of nano-Al2O3 addition on the microstructure and erosion wear of HVOF sprayed NiCrBSi coatings on AISI 304 steel. They concluded that there is no significant variation in the porosity, surface roughness and adhesion strength of the coating when added with 0.7 or 1.4 wt% of nano-Al2O3. But they recorded that micro hardness of the coating with addition of 1.4 wt% of nano-Al2O3 increased from 576HV0.3 to 748HV0.3 and the erosion resistance increased by 1.5 times. The mechanism of erosion observed were ploughing, micro cutting, indentation and type-I cutting. Chen et al [22] investigated the erosive behaviour of HVOF sprayed WC-Ni and WC-Cr2-Ni cermet coatings on substrate Cr18Ni9Ti. They observed that WC-Cr2-Ni cerment coatings exhibited better erosion resistance than WC-Ni coating and the substrate. The mechanism of erosion observed in the coating were cutting at low impact angle and pit formation at high impact angle. Upadhyaya et al [23] adopted a new thermal spray coating method i.e. High Velocity Oxy Liquid Fuel in order to deposit WC-10Co-4Cr coatings on narrow and complex area of hydro turbine parts. The coating procedure was carried out at two different spray angles of 45° and 70°. The coating obtained possessed a high micro hardness, high adhesion strength, low porosity and low surface roughness. CaviTech coating was carried on 304 stainless steel by HVOF thermal spraying process to study the corrosion and wear properties of the coating. Koga et al [24] characterized the coating by delamination and abrasive wear which possessed high cavitation erosion resistance and corrosion resistance in seawater like medium and dry sling wear performance. Praveen et al [25] successfully deposited NiCrSib/Al2O3 composite coating on AISI 304 stainless steel using plasma spraying technique and studied its erosive behaviour at impact angles of 30° and 90°. It was found that the coating exhibited improved erosion resistance of about 2.5 times in comparison to the uncoated steel at an angle of 30°. Andres et al [26] developed a test rig for carrying experiments on erosive wear and compared the erosive wear behaviour of uncoated 13Cr4Ni steel with HVOF sprayed WC-Co-Cr and plasma nitride surface treated steel. Both the processes showed significant improvement in the hardness and wear resistance. High Velocity Flame spray (HVFS) coating process was used to deposit nano structured and micron sized particles of Ni-40TiO2 and Ni-20TiO2-20Al2O3 on CA6NM steel [27]. It was found that Ni-40TiO2 coating possessed lower porosity, higher average microhardness and better bond strength than Ni-20TiO2-20Al2O3 coating. Sharma et al [28] developed a coating by mixing two different sizes (viz micron and nano) of Al2O3 reinforcement with 60 wt% Ni as the base powder using HVFS process on CA6NM steel. It was found that the coating was effective in minimizing the erosion rate than the bare steel. Sutar et al [29] studied the high temperature application of plasma sprayed coatings like pure red mud with varying weight% of flyash on mild steel and found that the reinforcement of flyash lead to a stronger bond with mild steel. Kumar et al [30] used two different thermal spraying processes i.e. HVAF and HVOF for depositing WC-Co-Cr. Miguel et al [31] compared the HVOF sprayed NiCrBSi coatings with Atmospheric Plasma Sprayed NiCrBSi coating and sprayed and fused coating. The results revealed that HVOF sprayed NiCrBSi coating showed best sliding wear resistance among all the three. Naveena et al [32] developed a mathematical model using regression analysis to study the slurry erosive behaviour of flyash-Al2O3 plasma spray coating on the substrate Al601. They varied experimental parameters like slurry concentration, rotational speed and impinging particle size. The coating exhibited better resistance to slurry erosion than the base material.

It is observed that different type of thermal spraying methods and different type of coating materials have been used by the researchers to study the effect of the erosion process, but there is no definitive recommendation. Hence in the present study an attempt has been made to study the behaviour of High Velocity Oxy Fuel (HVOF) sprayed NiCrBSi with mixed proportion of alumina i.e. NiCrBSi-5% Al2O3, NiCrBSi-10% Al2O3 and NiCrBSi-15% Al2O3 when exposed to an erodent like silica sand in water medium.

2. Experimentation

2.1. Specimen

Grade 420 stainless steel is chosen as the substrate material for the experimentation purpose as it has shown excellent results against solid particle erosion in comparison to the other steels [33]. The chemical composition of Grade 420 stainless steel is given in the table 1. Its hardness is 200–240 Hv in Vickers scale. Six specimens of the substrate steel of size 150 mm × 150 mm × 10 mm are taken for the coating purpose.

2.2. Coating powder

NiCrBSi (PAC 560 FHV) and pure Al2O3 (grain size: 22/5 microns) are used as coating materials with three different proportions of alumina i.e. NiCrBSi-5% Al2O3, NiCrBSi-10% Al2O3 and NiCrBSi-15% Al2O3.
2.3. Coating procedure

The coating of the samples is done at Metallizing Equipment Company Private Ltd. at Jodhpur, Rajasthan using High Velocity Oxy Fuel procedure is chosen for the coating purpose. The specimens are first grit blasted with Al₂O₃ particles to get a rough surface, in order to develop a better interlocking between the specimen and the coating \[34\]. The specimens are coated immediately after blasting as the nascent surfaces after sand blasting may develop oxide layers which detoriates the coating quality. The coating obtained is very dense and tightly bonded to the substrate because of high particle velocity, uniform heating and low dwell time. The coating parameters are listed in table 2.

2.4. Erosion test

The erosion tests are carried out in a Slurry Jet Erosion Tester TR-411 (figure 1) manufactured by DUCOM which confirms to ASTM-G-73 international standard test method. Instruments which works on the principle of repeated action of both the water jet and erodent. This test equipment is capable of producing a jet of slurry to strike on test specimen for eroding material from its surface under constant velocity and flux distribution throughout the duration of test. For experimentation the specimens (both coated and bare) are cut into size of 25 × 25 × 5 mm in wire EDM. The experimental parameters considered for experimentation are given in table 3.
3. Results and discussions

The erosive behaviour of the as sprayed coating is affected by the following factors such as properties of the coating materials and the striking particles, the fluid flow dynamics and the interaction of the striking particles with the coating materials.

The erosion rate \( (w) \) is expressed as,

\[
w = m_p K f(\alpha) V_p^n
\]

Where,

\( m_p \) = mass of particles striking the impact surface,
\( f(\alpha) \) = functional dependence of erosion rate on impact angle,
\( V_p \) = velocity with which the particle strikes the impact surface,
\( K \) = a constant and
\( n \) = velocity exponent.

\( K \) and \( n \) depend on the properties of the impact surface such as surface roughness, hardness, fracture toughness and elastic modulus. Other important factors which affect the erosion rate are the thickness of the coating, bond strength, residual stress, thermal expansion and compressive strength.

The impingement particles taken for the study are silica sand for slurry erosion tests. It has been established by Richardson [35] that if the erodent particles have higher hardness than the test specimen and their size exceeds critical dimension of 120–130 microns for ductile materials and 100–125 microns for brittle materials, then the intrinsic properties of the erodent particles will have least effect on the impingement erosion rate. Accordingly, under the study silica sand particles of 200 microns have been taken which goes well with the literature.

3.1. Micro structure and properties of the coating

The x-ray diffraction patterns of the sprayed coatings and the coating powders are shown in the figures 2(a), (b). There has been the presence of \( \gamma \) phase of Ni and \( \alpha \) phase of alumina in the feedstock powder. The change in the width and the height of the peaks in figure 2(b) indicates that slight amorphization has occurred due to high velocity oxy fuel coating process.

The Energy Dispersive x-ray Spectroscopy (EDS) images of the three coatings are given in figure 3 reveals the composition of the coatings and table 4 shows elements present in each coating obtained from the EDS.

The scanning electron microscope (SEM) images of the N5A, N10A, N15A coatings and uncoated 420ss are shown in figure 4. The thermal spraying processes are characterized by voids, pores, cracks, even melted and unmelted coating powder. In figures 4(a)–(c) voids, cracks, unmelted and melted particles can be clearly seen in the as sprayed coated samples. The SEM morphology image of the bare steel shown in figure 4(d) shows that no cracks appear on the surface of the steel which implies ductile behaviour of the steel.

The optical microscopy images of the polished cross section of the three coatings i.e. N5A, N10A and N15A are shown in figure 5. The images reveal lamella structures in the coatings which are parallel to the substrate.

The table 5 presents the thickness and the porosity of the coatings. The optical micrographs of the coatings are analyzed using the image analyzer. The porosity and thickness of the coatings are determined by analysing the image obtained from the optical microscope. The voids and the pores present in the coated samples are identified and their total area is calculated.

A diamond wheel cutter was used to cut the coated samples to specified sizes and a hot mounting press was used to mount the specimens in the resins for optical microscopy view of the as sprayed coated samples.

The surface roughness of the coating was measured in a surface roughness measuring apparatus of Taylor Hobson make. The measuring distance is fixed at 6 mm. The roughness value was obtained at different locations.
of the specimen. Five readings of each coating are taken and the values are recorded to find out the average of the Ra value. Table 6 gives the surface roughness (Ra) value of each coating.

The micro hardness value of the as sprayed coatings and the uncoated sample are given in table 7 which are measured in Vicker Microhardness tester. A load of 300 grams is applied for a dwell time of 10 s by a diamond indenter. Amongst the three coatings, N15A has the maximum micro hardness value as against N5A which has the minimum value. Similar results were obtained by other researchers [36–40].

The bond strength of the coatings is tested using Automatic Adhesion Tester (PosiTest AT-A), where an aluminium stud of diameter 10 mm is mounted on the coating surface, using an epoxy paste. The adhesion strength of the coatings ranged from 19.01 MPa to 22.37 MPa. Wang et al [41] reported a tensile bond strength of 22.9 MPa for HVOF sprayed Al₂O₃ + 75Ni coating and Yin et al [42] observed an adhesion strength of 28.8 MPa for Al₂O₃-Al plasma sprayed coating, while that of Al₂O₃ coating is 22.6 MPa.

Figure 2. X-ray diffraction patterns of (a) coating powders (b) coated samples.

Figure 3. EDS images of (a) N5A, (b) N10A and (c) N15A coated samples.
Figure 4. SEM micrographs of (a) N5A, (b) N10A, (c) N15A coated samples and (d) uncoated sample.

Figure 5. Optical microscopy images of (a) N5A, (b) N10A and (c) N15A coated samples.

Table 4. Elements present in (a) N5A, (b) N10A and (c) N15A coated samples.

| Element | N5A Weight % | N5A Atomic % | N10A Weight % | N10A Atomic % | N15A Weight % | N15A Atomic % |
|---------|--------------|--------------|---------------|---------------|---------------|---------------|
| B K     | 4.17         | 11.20        | 7.75          | 19.87         | 12.91         | 20.01         |
| C K     | 13.20        | 31.89        | 10.85         | 26.02         | 37.15         | 48.43         |
| O K     | 9.64         | 17.49        | 10.30         | 17.84         | 10.63         | 11.69         |
| Al K    | 6.36         | 6.83         | 8.57          | 7.75          | 10.05         | 8.99          |
| Si K    | 2.49         | 2.57         | 2.62          | 2.59          | 1.71          | 1.07          |
| Cr K    | 9.35         | 5.22         | 9.35          | 4.98          | 5.18          | 1.75          |
| FeK     | 2.75         | 1.43         | 2.78          | 1.38          | 1.76          | 0.55          |
| Ni K    | 45.26        | 22.37        | 41.97         | 20.75         | 16.94         | 7.18          |
| Au M    | 6.78         | 1.0          | 5.81          | 0.82          | 3.68          | 0.33          |
| Total   | 100.00       | 1.0          | 100.00        | 0.82          | 100.00        | 0.33          |
The fracture toughness of the coating is determined using equation (2)

\[
K_{IC} = 0.079 \left( \frac{P}{a} \right)^{3/2} \log \left( 4.5 \frac{a}{c} \right)
\]

(2)

where, ‘P’ is the indentation load, ‘c’ is crack length from the centre of the indent and ‘a’ is half diagonal length.

The bond strength and fracture toughness values of the coating are given in table 8.

### 3.2. Experimental results from slurry jet erosion test

The slurry erosion tests of the as sprayed coated and bare grade 420ss samples are carried out in a slurry jet erosion tester. The experimental parameters considered are impact angles (30°, 60° and 90°), impact velocity of 20 m s\(^{-1}\) and erodent size of 200 μm. Figures (a)–(d) shows the different as sprayed coated and uncoated samples exposed after erosion in a slurry jet erosion tester. The depressions on the eroded samples show the eroded areas. The different shapes of depression are due to the difference in the impact angle. The triangular shape of the depression on the samples is attributed to the 30° impact angle. The impact angles of 60° and 90° form elliptical and the circular shape depressions respectively on the eroded sample surfaces.

### 3.3. Effect of impact angle on erosion rate

The slurry jet erosion of the samples for three different impact angles (30°, 60° and 90°), impact velocity of 20 m s\(^{-1}\) and erodent size of 200 μm has been observed. The graphical presentation of the effect of impact angle on the erosion rate of the as sprayed coated and uncoated samples has been given in figure 7. The study of the graphs in figure 7 reveals that minimum wear has taken place in coated sample at 30° impact angle and maximum wear is visible when impact angle changes to 90°. The bare steel demonstrates minimum wear at 90° impact angle and maximum wear at 30° impact angle. This kind of occurrence is attributed to the ductile
property of bare steel. But it is important to note that at all impact angles N15A demonstrates higher wear resistance as compared to other coated samples and bare grade 420ss. The bare grade 420ss sample exhibits least wear resistance. Amongst the as sprayed samples, N15A sample shows best result against erosion rate whereas N5A sample shows poor resistance to erosion. When the erodent particles strike on the surface at acute angles of 30° and 60°, the components of the impact are responsible for the different erosion mechanism. The normal component of the impact is absorbed by penetrating into the matrix creating pits, pores/voids and craters. The horizontal component of the impact creates ploughing action on the surface due to the sliding action of the silt particles on the surface. As the particles slide on the surface they squeeze the coating/metal ahead and form ridges on the sides. Subsequent attack by incoming particles cause the ridges to flatten, fracture and form erosion debris. At high impact angle (90°) and low particle velocity the impact of the particle penetrates into the coating or the metal surface. This results in the formation of pits or dimples on the surface and the metal moves out by

![Figure 6. Photographs of (a) N5A, (b) N10A, (c) N15A coated samples and (d) uncoated sample after slurry jet erosion.](image)

![Figure 7. Erosion rate of N5A, N10A, N15A coated samples and uncoated sample at three different impact angles after slurry jet erosion.](image)
squeezing action. When the particles strike continuously on the surface, the ridges formed due to the squeezing of the metals are removed by fracture because of plastic deformation and flattening of ridges.

### 3.4. Erosion mechanism

The scanning electron microscope images of the eroded surfaces of the substrate and high velocity oxy fuel sprayed N5A, N10A and N15A coatings are presented in the figure 8. The effect of three impact angles of 30°, 60° and 90°, impact velocity of 20 m s\(^{-1}\) and the content of alumina in the coatings is analysed from the SEM images. The intensive observations of SEM images reveal mixed mode including both ductile and brittle. The erosion mechanism leads to material removal through micro cutting, ploughing, pitting action, splats and formation of voids and pores and it is greatly influenced by the impact angle.

The figure 8(a) shows the SEM micrograph of N5A coating subjected to slurry jet erosion at an impact angle of 30°, impact velocity of 20 m s\(^{-1}\) and erodent size of 200 \(\mu\)m. The micrograph demonstrates that the removal of material takes place in the form of splats by micro cutting and ploughing action. Figure 8(b) shows the micrograph of N5A coating at 60° impact angle. Micro cutting action and lip formation are visible on the surface of the eroded sample. Due to normal incidence angle of attack of silt particles on N5A coating the material is removed mostly in the form of splats as shown in figure 8(c).

The figure 8(d) represents the SEM micrograph of N10A coating subjected to slurry jet erosion at an impact angle of 30°, impact velocity of 20 m s\(^{-1}\) and erodent size of 200 \(\mu\)m. From the micrograph it can be concluded that the main mechanism of erosion is due to ploughing action of silt particles. Few splats are visible on the eroded surface. The micrograph of N10A coating at 60° impact angle as in figure 8(e) records the micro cutting action and material removal by splats on the surface which contribute to occurrence of erosion. But with the greater impact angle of 90°, as in figure 8(f), a greater number of splats are observed on the surface in comparison to other two previous cases.

Figure 8. SEM micrograph of N5A eroded sample at (a) 30°, (b) 60° and (c) 90° impact angle, N10A eroded sample at (d) 30°, (e) 60° and (f) 90° impact angle, N15A eroded sample at (g) 30°, (h) 60° and (i) 90° impact angle and grade 420ss eroded sample at (j) 30°, (k) 60° and (l) 90° impact angle, 20 m s\(^{-1}\) velocity and 200 \(\mu\)m erodent size.
Figure 8 shows the SEM micrograph of N15A coating subjected to silt erosion at an impact angle of 30°, impact velocity of 20 m s⁻¹ and erodent size of 200 μm. From the micrograph it can be inferred that micro cutting and ploughing action are the main erosion mechanism. At 60° impact angle as shown in figure 8(h) N15A shows micro cutting, ploughing along with lip formation on the surface. At 90° impact angle, the N15A coating after erosion in the surface shows more splats as in figure 8(i).

Figure 8(j) shows the SEM micrograph of grade 420ss subjected to silt erosion at an impact angle of 30°, impact velocity of 20 m s⁻¹ and erodent size of 200 μm. From the micrograph it can be observed that micro cutting mode of erosion has taken place plently along with lip formation on the surface of the uncoated specimen. Figure 8(k) shows the micrograph of uncoated sample of grade 420ss at 60° impact angle with micro cutting action. At normal impact angle the uncoated sample shows very few pores, pitting action and ploughing on the surface (figure 8(l)). All above performance of grade 420ss may be due to the ductile behaviour of the uncoated steel.

4. Conclusions

The following conclusions are drawn based on the results obtained.

1. The thickness and porosity of the coatings obtained from optical microscopy images range from 202.9 to 222.1 (μm) and 3 to 5 (%) respectively.

2. The N15A coating exhibits highest micro hardness value of 715 ± 31 HV₀.₃ followed by N10A (557 ± 22 HV₀.₃) and N5A (407 ± 15 HV₀.₃). The grade 420ss shows the lowest micro hardness value (272 ± 5 HV₀.₃).
3. The surface roughness ($R_z$) value of the coatings ranges from 3.6 to 6.3 $\mu$m which implies that very less pores and voids are present in the coating surfaces. In bare steel grade 420SS, the overall roughness is found to increase in all the exposed area after erosion. The roughness in the eroded area of the bare steel is about 0.5 $\mu$m to 1.1 $\mu$m whereas the polished bare steel before erosion had a roughness value ranging from 0.2 $\mu$m to 0.3 $\mu$m. Roughness depends upon the hardness and ductility of the base material. The surface roughness ($R_z$) value of the coatings after erosion ranges from 2.2 $\mu$m to 4.9 $\mu$m. In the coatings the surface becomes smoother after erosion. The roughness of the coatings depends on the powder properties and spray parameters such as particle size, temperature and velocity of spray.

4. All the coated surfaces exhibit the minimum wear at 30° impact angle and maximum at 90° impact angle. The erosion rate decreases by 6 times in N15A at 30° impact angle than at 90° impact angle. Similarly, 3 times and 2 times decrease in erosion rate is observed in N10A and N5A respectively.

5. The mechanisms involved in erosion of all the coated surfaces in slurry jet erosion testing process are removal of splats, lip formation, ploughing action and micro cutting. But in case of bare steel, the mechanism of material removal attributes to ploughing action, micro cutting and lip formation along with appearance of pores and craters.

6. The sprayed coatings in all the cases offer better erosion resistance than that of uncoated bare steel. N15A coatings at 30° impact angle exhibited 12 times better erosion resistance than uncoated grade 420 stainless steel. The surface coated with N15A powder is found to prevent erosion 2.4 times better than N10A and 4.1 times better than N5A coatings at 30° impact angle.

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