Erosion studies of Plasma-Sprayed NiCrBSi, Mo and Flyash Cenosphere coating

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Abstract. The erosion studies of plasma sprayed NiCrBSi / Mo / Flyash Cenosphere and NiCrBSi / Flyash Cenosphere on Superni 76 at room temperature for 30° and 90° impact angle were studied. The microstructure, adhesion properties, microhardness and porosity were investigated. Using SEM, EDS and EDAX techniques, the effect of phase change in the coating during the erosion was analyzed. The NiCrBSi/Mo/Cenosphere coating exhibits greater erosion resistance, and its loss of volume accounting nearly to 50% of the NiCrBSi/Cenosphere coating. Compared to a 90° impact angle, the smallest erosion loss was observed at 30°. The erosion process assessed using SEM micrographs showed that the coating suffered ductile fracture, exhibited acute deformation and had abnormal oxide cracks. The enhanced metal oxide has a shielding effect, can resist erosion, and thus has better erosion resistance.

Keywords: Impingement, Molybdenum, Hard facing, Cenosphere, Harness ratio.

1. Introduction

The phenomenon used to remove particles from the surface by the impingement is called erosion. The NiCrBSi coating has a high wear resistance and low coefficient of friction, used for hard bearing surfaces, abrasive wear resistant coatings and hardfacings. Among spray materials, nickel-based alloys are widely used because they show oxidation, high-temperature corrosion, good wear resistance, and low cost. NiCrBSi alloy is one of the better performing alloys and is usually used in mechanical components, such as rollers in hot plate cooling stations, rolling mills and pump bushings [1]. However, for example, there is still a need to improve the wear resistance of these alloys. In fact, the tribological properties of this coating seem to be strongly influenced by the nature, presence, morphology and quantity of the second phase [2]. The composition of silicon and boron reduces the melting point of these alloys, and gives them "self-melting" characteristics, especially suitable for spray coating [3]. Thermal spraying method is widely used processes for coatings, and finds applications in industries to a great extent.

Among the deposition processes, of which the most commonly used are arc wire spray, high speed oxygen fuel (HVOF) and flame spray plasma spray processes [4]. The advantage of plasma spraying technology is that it can process a variety of low-grade ores to get high value-added products, and can deposit metals, ceramics, and respective mixtures to produce a near-uniform composite coating with desired microstructures on substrate. In fact, thermal spraying is a process in which the coating material
is heated, melted and then pushed on to the substrate, forming coating. For this, metals, cermet, certain polymeric materials and ceramics can be used in the type of wires, rods or powders [5]. In spite of high temperature produced by the spray process, a portion of powder particles will melt incompletely because they spend short span during the stay in plasma stream. Due to drop in kinetic energy, temperature and oxidation cause uneven coatings with porosity more than 3% and reasonably poor adhesion between the substrate and the coating, this plays major role in tribological properties [6]. Porosity and micro cracks are undesirable micro structural characteristics as they enhance permeability in applications where corrosion resistance is required [7]. The coating quality based on several criterions, such as deposition rate, spray distance, angle (continuous or intermittent), combustion gas, deposition temperature, deposition technique, feed rate, process, sprayed particle size, the pressure applied and substrate temperature. All these criterions should be selected cautiously in order to achieve the most excellent coating performance for each purpose [8]. The best values of the above said criterions can provide the mechanical properties and best structure of the coating, which is necessary to meet the requirements.

In addition, few studies have added industrial waste, such as fly ash Cenosphere (hereinafter referred to as Cenosphere), to nickel-based composite coatings. Fly ash available in powder form from thermal power plants is available easily and treated as industrial waste. Fly ash is mainly composed of Fe2O3, SiO2, Al2O3 and traces of TiO2, CaO, etc. Among them Al2O3, SiO2, improves the resistance of wear of the coating. Using such industrial waste as a raw material for coatings can reduce the cost of coatings and minimize environmental pollution. This paper analyzes the structure, mechanical properties and corrosion properties of Cenosphere-Mo-NiCrBSi and Cenosphere-NiCrBSi coatings deposited by atmospheric plasma spraying (APS).

### 2. Materials and Methods

#### 2.1. Substrate

In the current work, Superni 76 alloy (ASTM Grade- Hastelloy X, Composition- Ni-18.5Fe-21Cr-2.5Co-9Mo-1Mn-0.1C-0.5W) is used as substrate. Superni 76, cold rolled plates are used in manufacturing turbine blades is purchased from Mishra Dhatu, Hyderabad. Sample of 25x25x3 mm3 and 25x20x3 mm3 dimensions were obtained from the plates with the help of milling machine and sharp edges removed by grinding. The powders NiCrBSi, Mo and Cenosphere with their weight percentages are blended using planetary ball milling spherical balls of tungsten carbide with a speed of 300 rpm, 10mm diameter for 10-minute interval to have correct mixture. The density of the coating is measured using pycnometer. Figure 1 presents the mechanically blended powder mixture of uniform distribution of Cenosphere and Molybdenum in NiCrBSi network clearly shows the Suitability and possibility of blending adopted mechanically.

![Figure 1](image-url)
2.2. Coating deposition
To ensure good bonding between substrate and coating, the surface has been grit blasted with alumina particles of 150μm grit size. The two powders, such as NiCrBSi/20%Mo/20%Cenosphere and NiCrBSi/40%Cenosphere, are deposited over the substrate. Plasma spray is carried out using METCO USA 3 MB equipment. In plasma spray, the feeder supplies the powder mixed with argon gas from compressor at desired pressure. In turn the powder melts in the plasma zone and gets deposited over the substrate. Coating deposited 20-25μm in each pass with deposition efficiency of around 40%. The thickness of the coating is measured using SEM. The variables selected throughout spray deposition are recorded in Table 1. JOEL-JSM-6380LA scanning electron microscope (SEM) used to examine the morphology of the coatings. ARTRAY, AT 130, JAPAN microscope is used to find out the porosity percentage.

In case of NiCrBSi/20%Mo/20%Cenosphere coating, due to the presence of Mo (20%), unmelted particles and as well as pores are observed as shown in Figure 2(a). Molybdenum forms MoO2 in the plasma zone which is well is known anti friction material. MoO2 has lower coefficient of friction than that of pure molybdenum. It also has the ability to prevent expansion and softening in extreme temperature environment. White region indicating NiCrBSi splats and grey region showing Mo phases. In the same way, Cenosphere particles are dispersed along the Ni alloy splat boundaries and become visible as dark grey region.

![Unmelted particle](image1)

![Melted matrix](image2)

![Semi-melted particle](image3)

(a) NiCrBSi/Cenosphere/Mo  
(b) NiCrBSi/Cenosphere

Figure 2. (a) and (b) SEM micrographs of top surface of composite coatings

| Table 1. Plasma spray parameters |
|---------------------------------|
| Argon  | Pressure | 100-120 psi |
| Hydrogen  | Pressure | 50 psi |
| Current  | 1350 amps |
| Voltage  | 60-70V |
| Powder feed  | 120-150 gm/min |
| Stand of Distance  | 100-125 mm |

2.3. Erosion Tests
ASTM G76-13 standard is used to carry out erosion tests using solid particle air jet erosion instrument (Ducom-TR-471-800) at room temperature. Diagrammatic presentation of erosion testing machine is shown in Figure 3, and conditions of erosion testing are listed in Table 2. The samples were acetone
cleaned, weighed using electronic balance with least count of 0.001g. The erosion testing is carried out for five cycles of five minutes each and for respective angle of impact. Once after each cycle, the eroded surfaces are cleaned using acetone, dried and found weight loss. The erosion rate is assessed by the ratio of mass loss of coating to mass loss of erodent. This procedure is continued until the gradual erosion rate accomplished a sustained value independent of testing time or erodent particles. The sustained value of incremental erosion rate is defined as steady state erosion rate. Volume loss due to erosion is determined by the difference of volumes before and after erosion.

Figure 3. Schematic of erosion test rig

Table 2. Erosion test parameters.

| Test Parameters                  | Variables |
|----------------------------------|-----------|
| Impact Angle in Degrees          | 30, 90    |
| Temperature in °C                | Room Temperature |
| Erodent Velocity in m/s          | 30        |
| Test Time (mins)                 | 5         |

3. Results and Discussion

3.1 Coatings Characterization

The microstructure of coating across the cross section of NiCrBSi/20%Mo/20%Cenosphere and NiCrBSi/40%Cenosphere is presented in Figure 3(a) and Figure 3(b). The individual splats produced by the melted, partially melted coating powders and their morphology are shown in Figure 4(a) and Figure (b) and are well bonded to the substrate. The coating thickness across the section is in the range of 250-320 μm. The percentage porosity of NiCrBSi/20%Mo/20%Cenosphere and NiCrBSi/40%Cenosphere coating is measured and found to be 2.90±0.20 and 3.70±0.21%, respectively. Figure 5(a) and 5(b) depicts EDS analysis and also element and percentage of weight, which shows splats rich in oxygen co-exists with silicon, iron and aluminium showing respective oxides. Chromium and nickel are distributed uniformly surrounding molybdenum and Cenosphere.
Figure 4. Cross-sectional SEM micrographs of composite coatings

(a) NiCrBSi/Cenosphere/Mo

(b) NiCrBSi/Cenosphere

Figure 5. (a) and (b) EDS analysis of NiCrBSi/Mo/Cenosphere with respective oxide percentages

| Element | Weight % |
|---------|----------|
| B       | 0.71     |
| O       | 21.00    |
| Al      | 6.46     |
| Si      | 5.21     |
| Mo      | 39.47    |
| Cr      | 5.11     |
| Fe      | 1.87     |
| Ni      | 20.17    |

(b) 

| Element | Weight % |
|---------|----------|
| B       | 38.55    |
| O       | 8.01     |
| Al      | 9.01     |
| Si      | 4.44     |
| Cr      | 7.43     |
| Fe      | 3.71     |
| Ni      | 28.85    |

3.2. XRD analysis

XRD model of the as-coated and powder samples of NiCrBSi/20%Mo/20%Cenosphere and NiCrBSi/40%Cenosphere composites is exhibited in Figure 6(a) and Figure 4(b), respectively. The phases in powder and as-sprayed coating were analyzed using x-ray diffractometer (DX GE-2P, JEOL,
JAPAN). For NiCrBSi/20%Mo/20%Cenosphere, the major peaks found in as-coated and powder patterns corresponds to Ni3B, MoNi4, Al8Mo3 and MoS2 and similarly minor peaks corresponds to NiCr2O4, Cr7C3, SiO2, Al2O3 and BMO2. In the case of NiCrBSi/40%Cenosphere the major peaks in powder and as-coated are SiO2, Al2O3, Ni2Si, Cr7C2, Ni3B and NiCrO4, the minor peaks correspond to Al2O3, Ni2Si, Cr7C2, Ni3B, NiCrO4. In case of NiCrBSi/20%Mo/20%Cenosphere, during oxidation Mo reacts with oxygen to form MoO2, which acts as a good self-lubricating agent.

![X-ray diffraction patterns](image)

**Figure 6.** (a) and (b) X-ray diffraction patterns of blended powders and as sprayed coating.

### 3.3 Micro hardness measurement

It is reported that in flight time is more in plasma spray than other spray processes due to which metal oxides are formed during oxidation. The hard reinforcement Al2O3 and SiO2 phases stay as it is even after Plasma spray. Micro hardness of coating and substrate is shown in Figure 7 and factors affecting microhardness are, non-uniformity in the cross section due to porosity, partially melted, melted and micro structural in homogeneity of the coating powders. The microhardness calculated with Clemex Vickers tester RS-232 (9-25 pins) under 200 g loads and a dwell time of 15 s. Average hardness value of NiCrBSi/20%Mo/20%Cenosphere and NiCrBSi/40%Cenosphere coatings was measured as 617 and
825 HV, respectively. It is noticed that the substrate hardness shows steady increment towards the interface due to strain hardening of grit blasting before coating and also compressive stresses induced at the interface during the impact of molten or partially melted particles in the spray process.

3.4 Erosion Behaviour
Erosion primarily depends on mass and number of particles impacting the surface with impact velocity. Brittle fracture and plastic deformation are the mechanisms by which the material is removed from the surface. Also depend on impact angle, velocity, environment and particle size. Therefore, if dominates plastic deformation, at low angles seen maximum wear. Similarly, at high impact angles brittle fracture occurs in which wear occurs at maximum. At low angles, Impact with round particle yield surface ploughing, but in case of angular particles yields are cutting. At 90° the damage usually occurs by chipping and cracking of surface material due to low strength of inter splats.

The erosion rate is obtained by the ratio of weight loss in the coating material to mass of eroded particles. During the initial cycle, the erosion rate was higher, and it was found that in subsequent cycles, the wear rate decreased. Sunderarajan and Roy [9] revealed that the erosion rate on the impact angle depends largely on the properties of the target.

Effect of volume loss and erosion rate with respect to two coatings is presented in Figure 8. The erosion volume loss at 90° impact angle is higher than that at 30° implying brittle mode of erosion. At lower impact of 30°, an erodent particle slide on the surface and ploughs the material.

3.5 Erosion Mechanism
At an impact angle of 30°, when the eroded particles hit with a high tangential force, severe plough marks appeared on the eroded surfaces of the coatings as shown in Figure 9(a) and 9(b). Plough, micro-cuts, and pits were found on the surface of eroded sample; substantiate the ductility and the removal of
the material in platelet form. Large grooves are formed by the impact of angular erodent with large particle size by ploughing mechanism. Ploughing mainly occurs in the softer nickel-based matrix area, and micro-cutting is caused by the influence of tiny corner erosion particles.

At 90° angle of impact, erodent particle directs vertically over the surface as shown in Figure 9(c) and 9(d). The constant impact creates indents, which causes the raised lips around the indentation. At high strain rate because of plastic deformation the raised lips are formed. The protective effect of the reinforcing agent (Mo) is weakened by the continuous impact of erosion, thereby weakening the boundary of the crack, resulting in the separation of the hard phase and leaving the crater.

Maximum volume loss experienced at higher angle of impact resulting in brittle mode of material loss. Cracks and craters were found because of localised strain resulting in brittle fracture. Since one-third area is bounded in plasma coating cracks are formed in the interface of hard particles and matrix. Further progress of erosion leads to lateral and radial cracks at subsurface and surface of coating. The cracks formed interlock with the non bonded area, leads to removal of lamellae.

4. Discussion
From the Figure 6d it is noticed more amorphous nature is accomplished in NiCrBSi / 40% Cenosphere coating. The high strain generated during the erosion is conducive to the formation of shear bands. In case of NiCrBSi / 20% Mo / 20% Cenosphere coating, MoO2 can be used as a surface active element together with other molten particles, thereby greatly reducing the surface tension by dispersing along the splash boundary. Due to surface tension good wettability of MoO2 formed which enhances bonding between splats yield in superior erosion performance of NiCrBSi / 20% Mo/ 20% Cenosphere coating. Found less erosion volume in NiCrBSi / 40% Cenosphere coating as compared to that of NiCrBSi / 20% Mo / 20% Cenosphere.
5. Conclusions

1. Plasma spraying is used to obtain thick coating with thickness of 210 and 375 μm respectively for NiCrBSi/20%Mo/20%Cenosphere and NiCrBSi/40%Cenosphere coatings.
2. Found the erosion rate is minimum at 30° angle of impact and is maximum at 90° when alumina is used as erodent.
3. Mo surface activity is the most important factor, because it minimizes the uniformity of similar molten particles in the spraying process and make the particles dispersed along the splat boundary of the coating.
4. Thus, NiCrBSi/20%Mo/20%Cenosphere coating exhibited good resistance to volumetric erosion at both 90° and 30° impact angle than NiCrBSi/40%Cenosphere coating.
5. At lower impact angles, plough, micro-cut, and hard-phase pullout features were observed on the eroded surface of the coating, indicating that ductile type of fracture.

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