Abstract

Slurry erosion performance of detonation gun (D-gun) sprayed ceramic coatings (Stellite-6 and Cr$_3$C$_2$-25NiCr) on 13Cr4Ni steel has been investigated. Commercially available silica sand was used as the abrasive media in a high speed erosion tester. Behavior of coated and uncoated steel has been observed at two different angles (30° and 90°) under a set of significant factors such as slurry concentration, erodent size and rotational speed. The analysis of eroded samples was done using SEM. SEM of the eroded specimens showed mixed (brittle and ductile) mode of erosion mechanism. It has been observed that the Stellite-6 coating performed better than Cr$_3$C$_2$-25NiCr and uncoated steel when comparing them at 30°. On the other hand, uncoated 13Cr4Ni showed good performance at 90° in comparison to coatings.

Keywords

Slurry Erosion, SEM, EDS, Detonation Gun, High Speed Erosion Tester

I. Introduction

Due to heavy silt content in water, the underwater parts of turbines like turbine blades, needles and nozzles get eroded and the turbine efficiency reduces and leads to high revenue loss in the hydro plant per year and such slurry wear leads to degradation of machinery performance and shortened service life [1]. Erosion is common phenomenon of underwater parts in turbines due to the impact of hard particles [2]. Silt problem occurs in mainly hilly areas, especially during the rainy seasons. Due to the increase in concentration of solid particles, filtration process is not possible [3]. Water contains Quartz, Tourmaline, Garnet, Zircon, etc of Hardness 7 on MHO scale [4]. These sediments are formed due to the fragmentation of rocks, erosion of land and land sliding because of heavy rains during the monsoon period in the Himalayan region of India [5]. Conventional steels used in hydro power plants are not able to sustain the slurry erosion problems that exist in hydro turbines [6-7]. To enhance the surface performance and durability of engineering components exposed to different forms of wear such as abrasion, erosion and corrosion thermal spray techniques are versatile means of developing a wide variety of coatings/protective layers [8–9]. Detonation gun (D-gun) spray process is a thermal spray coating process, which provides an extremely good adhesive strength, low porosity, coating surface with compressive residual stresses, low oxide contents and high intersplat strength [10-11]. The D-gun spray process involves the impingement of powdered materials through a water-cooled barrel with the supersonic speed on the surface of substrate. The two phase mixture of coating are heated to plasticity and impinges against a target substrate, where the high temperature, high velocity coating particles bond into the surface of substrate and a mechanical interlocking and microscopic welding may take place [12]. To resist wear ceramic materials are now commonly employed in the form of coatings. Due to high melting point of the ceramic powders which require a high temperature jet to get deformed during coating formation, these coatings are usually deposited by atmospheric plasma spraying [13]. However, plasma sprayed coatings are possess more porous and brittle nature than high velocity thermal-sprayed coatings [14-15]. But due to close interlamellar contacts and small porosity, the high-velocity combustion spraying techniques provides greater hardness [16-17]. This is why several efforts have been undertaken to use these high-velocity spray techniques like to spray oxides Detonation gun spraying is mainly used [18]. Under actual service conditions it is often a difficult task to evaluate slurry erosion behavior of materials due to interactive effects of different parameters such as slurry concentration, velocity and properties of abrasive medium on wear rate. Accelerated erosion testing of materials can be performed by increasing load, velocity and other operational parameters in a laboratory test rig, where real contact conditions can be simulated. Objective of this study is to investigate the slurry erosion behavior of D-gun-sprayed Stellite-6 and Cr$_3$C$_2$-25NiCr coatings on CF8M steel under the hydro accelerated conditions by using a high speed erosion test rig.

II. Experimentation

A. Substrate Material

13Cr4Ni stainless steels which are commonly used in hydropower plants were selected for this research study. Chemical composition of 13Cr4Ni steel is given in Table 1. Rectangular specimens of 10 mm X 10 mm were prepared from the steel.

B. Coating Deposition

The feedstock powders used in this study were commercially available Stellite-6 and Cr$_3$C$_2$-25NiCr powders, details of which are given in Table 2. The morphology of powder along with EDS has been studied by scanning electron microscopy (JEOL JSM-6610LV). Samples were then coated by D-gun spray process available with SVX Powder M Surface Engineering Pvt. Ltd., Noida, India. The coatings were deposited using the standard process parameters reported in Table 3. Thereafter, the cut sections were mounted in transoptic powder using hydraulic hot mounting press (Model: Bainmount H, Chennai Metco Make). Subsequently, the mounted specimens were polished manually using SiC emery papers of 400, 600, and 1000 grit sizes. Finally, the specimens were mirror polished on a velvet cloth polishing machine with alumina powder suspension. Specimens were then washed and dried before being examined. Mirror-polished specimens were examined under the SEM.
Table 1: Chemical composition of 13Cr4Ni Stainless Steel (wt %)

<table>
<thead>
<tr>
<th>Steel</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>Cr</th>
<th>Ni</th>
<th>N</th>
<th>S</th>
<th>Cu</th>
<th>Co</th>
<th>P</th>
<th>Mo</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>13Cr4Ni</td>
<td>0.06</td>
<td>0.74</td>
<td>1.16</td>
<td>13.14</td>
<td>3.9</td>
<td>--</td>
<td>0.014</td>
<td>0.088</td>
<td>0.035</td>
<td>0.015</td>
<td>0.61</td>
<td>Bal.</td>
</tr>
</tbody>
</table>

Table 2: Nominal Composition (Mass %) and Physical Properties of Coating Powders

<table>
<thead>
<tr>
<th>Powder (Commercial Code) / Make</th>
<th>Composition</th>
<th>Morphology</th>
<th>Particle Shape</th>
<th>Size</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stellite-6 / DeloroStellite</td>
<td>Co Base Cr 27-32% W 4-6% Cr 0.9-1.4% Others Ni, Fe, Si, Mn, Mo</td>
<td>gas atomized powders</td>
<td>Spherical</td>
<td>53/10 µm</td>
<td>36-45 HRC 380-490 HV</td>
</tr>
<tr>
<td>Cr3C2-25Ni4Cr , AMPERIT®-584.054 / H.C. Starck</td>
<td>Cr 9-11% Cr 65.9 – 73% Ni 18-22% Fe_{max} 0.5% O_{max} 0.6%</td>
<td>Agglomerated sintered</td>
<td>Almost Spherical</td>
<td>45/10 µm</td>
<td>775–1200 HV</td>
</tr>
</tbody>
</table>

Table 3: Process parameters for D-gun spray process

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Stellite-6 Coating</th>
<th>Cr3C2-25NiCr Coating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen flow rate (O₂)</td>
<td>3120 SLPH</td>
<td>2720 SLPH</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.2 MPa</td>
<td>0.2 MPa</td>
</tr>
<tr>
<td>Acetylene flow rate (C₂H₂)</td>
<td>2400 SLPH</td>
<td>2400 SLPH</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.14 MPa</td>
<td>0.14 MPa</td>
</tr>
<tr>
<td>Nitrogen flow rate (N₂)</td>
<td>1040 SLPH</td>
<td>960 SLPH</td>
</tr>
<tr>
<td>Pressure</td>
<td>0.4 MPa</td>
<td>0.4 MPa</td>
</tr>
<tr>
<td>Spray angle</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td>Spray distance</td>
<td>150 mm</td>
<td>165 mm</td>
</tr>
<tr>
<td>Power</td>
<td>450 VA</td>
<td>450 VA</td>
</tr>
</tbody>
</table>

C. Slurry Erosion Testing

To study the slurry erosion behavior of coated and uncoated steel, a high speed erosion tester was used (DUCOM TR401, Bangalore make). This set up consists of slurry abrasion chamber, slurry tank, rotor, control panel, 3 phase induction motor which is shown in fig. 1. Slurry abrasion chamber encloses the specimens and slurry. Slurry tank is cylindrical vessel of stainless steel in which slurry is prepared by mixing water and sand of required particle size and in required proportion. Rotor of the tester is used to mount specimen and it is enclosed in slurry chamber. 12 specimens can be placed on the rotor, which is main advantage of this tester. Control panel consists of controls for rotor speed, setting time for test, start and stop buttons. For recirculation of slurry 3 outlet pipes and 3 inlet pipes are provided between slurry chamber and tank. In the starting specially designed specimen holders are mounted on the appropriate place in chamber and adjusted at required angles for rectangular specimen. Then specimens are mounted in specimen holders. Now slurry chamber is closed by lifting the screw jack and tightening the nuts at four places to make it air tight. After setting rotational speed and time for a run, motor is started. Due to rotation of rotor vacuum is created and slurry enters the slurry chamber from slurry tank through the inlet pipes. After rotation and time for test, the specimens are removed from the rotor assembly, brushed gently and cleaned with acetone to remove attached sand particles if any. The specimens were weighed before and after each slurry erosion cycle. The loss in mass of each specimen was recorded with the help of precision micro weighing scale.
Fig. 1: Experimental Setup of High Speed Erosion Tester (DUCOM TR401)

Fig. 2: Schematic Diagram Showing Interactions of a Rectangular Specimen With the Slurry Particles in the Slurry Chamber at 30° and 90°
having an accuracy of 0.1 mg. As erosion is a surface phenomenon so the surface area of each specimen was calculated by measuring the length and width at two places, taking their mean for getting average length and width of specimen with the help of digital vernier caliper of least count 0.01 mm.

Specific mass loss was calculated using

$$\text{Specific mass loss} = \frac{\text{mass loss (g)}}{\text{Exposed surface area (m}^2\text{)}} \times 10^6$$

The slurry erosion process was repeated for six cycles, each cycle of duration 1 hour. The results have been plotted as cumulative mass loss per unit area in (g/m$^2$) versus time of exposure (h) to ascertain the kinetics of slurry erosion behavior of coatings and substrate.

### III. Results and Discussion

#### A. SEM and EDS Analysis of Coating Powders and Coating as Sprayed

SEM and EDS analysis of Stellite-6 powder is shown in fig. 3. From SEM analysis it can be observed that the particles are of spherical shape. From EDS analysis it is clear that it is Cobalt based alloy containing chromium content also.

SEM and EDS analysis of Cr$_3$C$_2$-25Ni4Cr is shown in figure 4. It can be seen that the particles are almost spherical and they are Agglomerated sintered and powder containing the chromium, carbon as well as nickel content.

![Fig. 3: SEM and EDS Analysis of Stellite-6](image)

![Fig. 4: SEM and EDS Analysis of Cr$_3$C$_2$-25Ni4Cr](image)
In fig. 5, surface morphology of Stellite-6 is shown. The coating seems to contain fine grains dispersed in the matrix. The grains appear as round white particles, whereas very dark small round spots are the micro-pores.

The cross-sectional view of the coated sample of Stellite-6 (Fig. 6) shows distinctly the coating layer, interface, and the substrate. The interface, by and large, seems to be defect free showing nearly a continuous contact of coating and substrate. The coating thickness is found to be 100-150 µm. Some micro-voids along the splat boundaries of the coating are also present.

Fig. 5: Surface SEM Analysis of the D-Gun-Sprayed Stellite-6

In fig. 7, surface morphology of Cr$_3$C$_2$-25Ni4Cr is shown. The cross-sectional view of Cr$_3$C$_2$-25Ni4Cr is shown in figure 8. Similar to Stellite-6 coating, this coating is also found to be defect free except few micro pores. The thickness of coating is found to be 150 to 200 µm.

Fig. 6: Cross-Sectional SEM of Stellite-6 on 13Cr4Ni

Fig. 7: Surface SEM Analysis of the D-Gun-Sprayed Cr$_3$C$_2$-25Ni4Cr

Fig. 8: Cross-Sectional SEM of Cr$_3$C$_2$-25Ni4Cr on 13Cr4Ni

**B. Slurry-Erosion Testing**

Cumulative mass loss versus time plots for D-gun sprayed Stellite-6, Cr$_3$C$_2$-25Ni4Cr and uncoated 13Cr4Ni at 30° is shown in figure 9. It has been observed that cumulative mass loss for uncoated steel is higher than the coatings at 30°. It can be observed that as the time increases the cumulative weight loss per unit area increases for coatings as well as for uncoated steel. After a run of 6 hours overall specific weight loss for Stellite-6, Cr$_3$C$_2$-25Ni4Cr and uncoated 13Cr4Ni at 30° is 187.43 g/m², 386.13 g/m² and 699.06 g/m² respectively. This indicated that coating is useful to develop erosion-resistance in the base steel at 30°.

Fig. 10 shows Cumulative mass loss versus time plots for D-gun sprayed Stellite-6, Cr$_3$C$_2$-25Ni4Cr and uncoated 13Cr4Ni at 90°. At this angle cumulative mass loss also increases for coatings as well as for uncoated steel. But cumulative mass loss for uncoated steel is less as compared to both coatings. After a run of 6 hours overall specific weight loss for 13Cr4Ni is 84.94 g/m², for Stellite-6 is 283.01 g/m², and Cr3C2-25Ni4Cr for 520.62 g/m². This indicates that coating is not much useful on steel at 90°.

Fig. 11 shows the comparison between Stellite-6 at 30° and Stellite-6 at 90° on cumulative mass loss per unit area versus time graph. With the increase in time weight loss per unit area of Stellite-6 increases for both angles. After 6 hour run overall specific weight loss for Stellite-6 at 30° is 187.43 g/m² and for Stellite-6 at 90° coating it is 283.01 g/m². Specific weight loss for Stellite-6 at 90° is 1.5 times specific weight loss for Stellite-6 at 30°.

Cumulative mass loss per unit area of Stellite-6 at 30° and 90° is shown in fig. 12. From the graph it can be seen that Stellite-6 performed better at 30° as the maximum weight loss for Stellite-6 at 30° is less than the Stellite-6 at 90°. The maximum weight loss for Stellite-6 at 30° is 187.43 g/m² and at 90° it is 283.01 g/m².
In fig. 13 there is a comparison between cumulative mass loss per unit area of Cr$_3$C$_2$-25NiCr at 30° and 90°. More erosion of Cr$_3$C$_2$-25NiCr takes place at 90°. The maximum weight loss for Cr$_3$C$_2$-25NiCr is 386.13 and 520.62 g/m$^2$ at 30° and 90° respectively after a 6 hour run in slurry erosion chamber of high speed tester. The ratio of maximum weight loss at 30° to 90° comes out 1.34.

C. Material Removal Mechanism

In the present study rectangular specimens were rotated in high speed tester containing the slurry. This slurry may cause erosion and abrasion damage of the specimen surfaces. In the present study the specimen was placed at two different angles i.e. 30° and 90°. When specimen is at 90° there will be only normal interaction of sand particles with surface of specimen therefore this interaction can make the material to fail by fatigue or under plastic deformation. Whereas when specimen is at 30° then sand particles will hit surface tangentially. Hitting force can be divided into two components i.e. Tangential component which is parallel to the surface of specimen has a cutting effect at the surface. Whereas, the perpendicular component may be the reason of fatigue failure or may cause plastic deformation. Therefore it can be thought that slurry erosion of specimen at 90° will be due to the fatigue alone whereas at 30° it can be thought that slurry erosion of the specimens is occurring simultaneously by cutting abrasion and deforming abrasion. To investigate the material removal mechanism, all eroded specimen were examined under SEM. Figure 14 and 15 shows the SEM analysis of eroded 13Cr4Ni at 30° and at 90° respectively. SEM analysis of eroded Stellite-6 is shown in figure 16 and 17 at 30° and at 90° respectively. SEM analysis of eroded Cr$_3$C$_2$-25NiCr at 30° and 90° is shown in fig. 18 and 19 respectively.
It can be observed from SEM analysis of 13Cr4Ni at 30° that only ploughing effect is dominating in this case. At 30° in coatings there are the evidence of removal of grains, pit formation and brittle signatures. At 90° in coatings pit formations are more as compared to 30°. Also in Cr₃C₂-25Ni4Cr there are more pits as compared to Stellite-6 and 13Cr4Ni at 30° and 90° due to the more hardness of Cr₃C₂-25Ni4Cr. Due to more hardness of Cr₃C₂-25Ni4Cr the material is removed in the shape of flakes.
IV. Conclusion
Based on the results obtained from this study, the following conclusions may be drawn:

1. The erosion resistance of coatings and substrate steel at 30° is found to be in the following manner:
   Stellite-6 > Cr$_3$C$_2$-25Ni4Cr > 13Cr4Ni > Cr$_3$C$_2$-25Ni4Cr

2. The erosion resistance of coatings and substrate steel at 90° is found to be in the following manner:
   13Cr4Ni > Cr$_3$C$_2$-25Ni4Cr > Stellite-6

3. Performance of substrate 13Cr4Ni steel is better at 90° when compared with 30°.

4. Stellite-6 at 30° is having better erosion resistance as compared to 90°.

5. Cr$_3$C$_2$-25Ni4Cr also performed better at 90° when compared with 30°.

6. Dominating material removal mechanism for the material at 90° was found to be Fatigue and brittle failure whereas ploughing and fatigue failure is dominated for the material at 30°.

References


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