Erosive wear of a surface coated hydroturbine steel

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Abstract. In the present investigation, stellite-6, $\text{Cr}_3\text{C}_2\text{-NiCr}$ and WC-Co-Cr coatings were deposited by D-Gun on a hot rolled 21Cr-4Ni-N steel meant for fabrication of hydro turbine underwater parts. The coatings have been characterized for microstructure, porosity, microhardness and crystalline nature. The erosion experiments were carried out using an air jet erosion test rig at a velocity of 120 ms^{-1} and impingement angles of 30° and 90° . Silicon carbide particles of size ranging between 500 and $700\text{ }\mu\text{m}$ were used as erodent. Scanning electron microscopy (SEM) technique was used to analyse the nature and mechanism of erosion. Erosion behaviour is observed to be influenced largely by the nature and extent of porosity in the surface coatings.

Keywords. D-Gun sprayed coating; porosity; stellite-6; $\text{Cr}_3\text{C}_2\text{-NiCr}$; erosion.

1. Introduction

The loss of material caused by the impingement of tiny solid particles, which have a high velocity and impact on the material surface at defined angles, is called erosive wear (Guo *et al* 1995). Erosion is a serious problem in many engineering systems, including steam and hydro turbines, pipelines and valves used in slurry transportation of matter, and fluidized bed combustion systems (Kosel 1992). Coatings of wide variety of materials are commonly applied for many purposes, especially to improve tribological performance; that include the enhancement of mechanical properties, visual appearance or corrosion resistance and optical properties. It has been reported that the thermal spray is a technique that produces a wide range of coatings for various applications (Herman and Sampath 1996). Erosion tests on coatings have been widely reported (Barbezat *et al* 1993; Takeda *et al* 1993; Wang 1993; Shipway and Hutchings 1995; Hearley *et al* 1999; Wang and Lee 2000; Mishra *et al* 2006; Sidhu *et al* 2007). The mechanisms of coating damage in such tests depend on the coating material and its thickness, the properties of the interface, the substrate material and the test conditions (Shipway and Hutchings 1995).

Among the commercially available thermal spray coating techniques, detonation spray and high velocity oxy fuel spray are the best choices to get hard, dense and consequently wear resistant coatings (Barbezat *et al* 1993; Wang 1993; Semenov and Cetegen 2002). Thermally

sprayed coatings of thickness, $200\text{--}400\text{ }\mu\text{m}$, offer an effective and economic method of conferring wear resistance without compromising other attributes of the component. Detonation Gun (D-Gun) spraying has been shown to be one of the best methods for depositing coatings because of the higher velocities and lower temperatures experienced by the powder particles (Fagoaga *et al* 1998; Wang *et al* 2000).

In an earlier paper (Chauhan *et al* 2008), it has been reported that hot rolled 21-4-N austenitic steel possesses excellent erosion resistance in comparison to 13Cr-4Ni steel (CA6NM), which finds wide application in hydro turbine underwater parts. In this work, attempts have been made to investigate the erosion behaviour of D-Gun sprayed stellite-6, $\text{Cr}_3\text{C}_2\text{-NiCr}$ and WC-Co-Cr coatings on hot rolled 21-4-N steel substrate. The analysis of eroded surfaces as well as coatings has been done using scanning electron microscope (SEM).

2. Experimental

2.1 Substrate material

The substrate material selected for the study was a nitronic steel (termed as 21-4-N steel), which was procured from M/s Star Wire (India) Ltd. Ballabgarh (India) in the form of hot rolled bars of $40 \times 40\text{ mm}$ cross section. The chemical composition of the substrate material was (wt%): 0.56C–9.9Mn–23.42Cr–4.28Ni–0.38N–0.25Si–balance Fe. The specimens measuring $40 \times 40 \times 10\text{ mm}$ were cut from the bars. The specimens were polished and grit blasted before subjecting to coating by D-Gun.

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2.2 Surface coatings

Three types of powders were used in the study, the chemical compositions of which are reported in table 1.

D-Gun spray equipment having horizontal orientation was used for coating of the samples at the worksite of M/s Sai Surfacing Co. Hyderabad (India). The D-Gun spraying process parameters are given in table 2.

2.3 Characterization of D-Gun sprayed coatings

The microstructural features of the coated specimens were studied using optical microscope. Porosity of coatings was measured using a Zeiss Axiovert 200 MAT inverted optical microscope fitted with imaging software, Zeiss Axio Vision 4.1. Microhardness of the coatings was measured by Leitz's Hardness Tester Mini Load-2. Two hundred gram load was provided to the needle for penetration and the hardness value was determined based on the relation:

$$HV = 189.03 \times 10^3 \times (F/d^2),$$

where F is the load in gram, and d the mean of the indentation diagonal length in μm . For each hardness value, an average of ten measurements was taken. The XRD analysis was carried out using a Bruker AXS D-8 Advance Diffractometer with $\text{CuK}\alpha$ radiation.

2.4 Erosion testing

Erosion tests were performed in a near sonic high velocity gas blast erosion rig facility developed as per standard followed by Wood and Wheeler (1999). The details of the design of test rig can be found in an earlier paper (Chauhan *et al* 2008). The erodents were accelerated down a 16 mm diameter stainless steel tube, 1 m in length, to

impact on the sample. Particle velocity of 120 ms^{-1} at a constant feed rate of 5 g min^{-1} was employed. The flux rate was kept below the level at which particle-particle interactions begin to significantly reduce the erosion rate (Shipway and Hutchings 1994). Dry compressed air was mixed with the particles, which were fed at a constant rate from a particle feeding hopper in the mixing chamber and then accelerated by passing the mixture through a tungsten carbide converging nozzle of 8 mm diameter. These accelerated particles impacted the specimen, which could be held at various angles with respect to the impacting particles using an adjustable sample holder.

The studies were performed on uncoated as well as coated specimens for the purpose of comparison. The erosion test conditions utilized in the present study are listed in table 3. A standard test procedure was employed for each erosion test. The samples were cleaned in acetone, dried, weighed to an accuracy of $1 \times 10^{-4} \text{ g}$ using an electronic balance, eroded in the test rig for 10 min and then weighed again to determine weight loss. The ratio of this weight loss to the weight of the erodent particles causing the loss (i.e. testing time $\times$ particle feed rate) was then computed as the dimensionless incremental erosion rate. The erosion rate (g/g) versus erosion time (min) was plotted to compare the erosion rate of the substrate as well as the coatings. SEM study of eroded surfaces was conducted using LEO 435 VP scanning electron microscope at an accelerating voltage of 15 kV.

3. Results and discussion

3.1 Microstructures and XRD spectra

Figure 1 shows the XRD spectra and optical micrograph of stellite-6 coating. From the peaks in XRD spectra (figure 1a), it is observed that the stellite-6 coating consists of Cr_{23}C_6 and Co (γ or fcc), of which chromium carbide (Cr_{23}C_6) is the dominating hard phase. The microstructure of stellite as shown in figure 1b consists of fine chromium carbides in the austenitic matrix of Co. Some of the dark etching regions may also be due to porosity. Identical observation has been reported by Singh *et al* (2005)

Table 1. Composition of coating powders.

Coating material	Composition (wt%)
Stellite-6	30 Cr–5Fe–6W–1C–Co (Bal)
Cr_3C_2 –NiCr	75 Cr_3C_2 –25NiCr
WC–Co–Cr	WC–10Co–4Cr

Table 2. D-Gun process parameters.

Particle size	35–45 μm
Spray spot diameter	25 mm
Spraying distance	200 mm
Spraying atmosphere	Air
Thickness per shot	5–6 μm
Shots/s	3
Total coating thickness	300 μm

Table 3. Erosion parameters.

Erodent material	Silicon carbides
Particle size (μm)	500–700
Particle velocity (ms^{-1})	120
Air pressure (kPa)	196
Impact angle ($^\circ$)	30 and 90
Nozzle diameter (mm)	8
Test interval (min)	10
Working distance (mm)	10

for plasma sprayed stellite-6 coating on Fe-based super-alloy.

Figure 2 shows the XRD spectra and optical micrograph of the Cr_3C_2 -NiCr coating. From the peaks in XRD spectra (figure 2a), it is observed that the Cr_3C_2 -NiCr coating is made up of carbides and oxide phases, including Cr_3C_2 , Cr_3Ni_2 and Cr_2O_3 . In HVOF Cr_3C_2 -NiCr coating, apart from Cr_3C_2 carbide particles, the carbides Cr_7C_3 and Cr_{23}C_6 might be also present according to the reported results through X-ray diffraction analyses (Ji *et al* 2006). It is likely that these carbides are formed through decarburization of Cr_3C_2 . However, it is further pointed out that the presence of Cr_7C_3 and Cr_{23}C_6 in the as-sprayed Cr_3C_2 -NiCr coating cannot be proven solely by X-ray diffraction approach because their main diffraction peaks coincide with the lines referring to the NiCr and Cr_3C_2 . As seen in figure 2b, the microstructure of Cr_3C_2 -NiCr coating is characterized by bright phases as the binding matrix in which the dark/gray regions are carbides of type, Cr_3C_2 and/or chromium oxide (Cr_2O_3). The very dark points observed in the binding matrix may be due to porosity. Similar observations have been reported by Wang *et al* (2000).

Figure 1. (a) XRD spectra and (b) optical micrograph of stellite-6 coating.

Figure 3 shows the XRD spectra and optical micrograph of the WC-Co-Cr coating. From the peaks in XRD spectra (figure 3a), it is observed that the WC-Co-Cr coating contains $\text{Co}_3\text{W}_3\text{C}$, WC, W_2C and CrCo, of which $\text{Co}_3\text{W}_3\text{C}$ and WC are the major hard phases. The presence of W_2C phase in this coating indicates the decarburization of WC during coating process. Chromium addition to WC-Co inhibits the decarburization of WC to metallic tungsten. Similar XRD peaks have also been reported by Sahraoui *et al* (2003) and Zhang *et al* (2007). As seen in figure 3b the microstructure of WC-Co-Cr coating consists of carbides well distributed and bonded within the Co based binding matrix. Bright/gray areas indicate binding matrix in which WC is dissolved in solution. Dark particles of carbides are seen in blocks of bright etching binding matrix. Identical observations have been reported by Murthy *et al* (2001).

3.2 Porosity and microhardness measurements

The average porosity and microhardness of the D-Gun sprayed coatings are given in table 4. The average poro-

Figure 2. (a) XRD spectra and (b) optical micrograph of Cr_3C_2 -NiCr coating.

sity of the D-Gun sprayed coatings is found to be in the range of 0.03–0.29%. The stellite-6 coating exhibits highest hardness of 1098 HV, as also reported by Zhang (2003) and Zhao *et al* (2004). This coating, however, suffered from maximum porosity of 0.29%. The porosity as well as microhardness of the stellite-6 coating is observed to be highest of the three coatings. The porosity of WC–Co–Cr coating is found to be lowest of the three coatings, whereas the minimum value of the average microhardness is shown by Cr_3C_2 –NiCr coating. The measured values of porosities of Cr_3C_2 –NiCr and WC–Co–Cr coatings in this investigation are much less as compared to the observations of Sahraoui *et al* (2003) for HVOF coatings.

Figure 3. (a) XRD spectra and (b) optical micrograph of WC–Co–Cr coating.

Table 4. Porosity and microhardness of coatings.

Coating material	Average porosity (%)	Microhardness (HV _{0.2})
Stellite-6	0.29	1098
Cr_3C_2 –NiCr	0.10	824
WC–Co–Cr	0.03	990

3.3 Erosion rate

Erosion tests were conducted at impingement angles of 30° and 90° using silicon carbide particles as erodent. It

Figure 4. Erosion rate (g/g) as a function of erosion time for substrate material as well as for various coatings at impingement angles (a) 30° and (b) 90°.

Figure 5. A histogram illustrating cumulative weight loss of substrate (hot rolled 21-4-N steel) and different D-Gun sprayed coatings.

Figure 6. Scanning electron micrographs of eroded surfaces after 120 min of erosion test at 30° impingement angle of (a) substrate, (b) stellite-6, (c) $\text{Cr}_3\text{C}_2\text{-NiCr}$ and (d) WC-Co-Cr coatings.

is seen that at both impingement angles the erosion rate of the substrate material first increases rapidly and then becomes almost constant. The erosion rates of coated specimens at 30° impingement angle also increases rapidly in the beginning and become almost constant (figure 4a). At 90° impingement, however, the erosion rates of coatings initially decreases rapidly before attaining steady state values, as seen in figure 4b. It is also observed that at both 30° and 90° impingement angles, the stellite-6 coating exhibits, in general, the maximum erosion rate. In all cases the 30° impingement angle yields lower erosion rates in comparison to 90° impingement. The lowest erosion rate is observed in the WC-Co-Cr coating at 30° impingement angle.

The erosion damages in terms of cumulative weight loss at the end of erosion test duration of 120 min are given in bar chart form in figure 5, which also shows lower erosion damages at 30° impingement angle. At 30° impingement angle the erosion loss is primarily due to shear cutting of surface material, whereas at 90° impingement angle erosion damage is due to strain hardening and embrittlement of target material. The erosion at 90°

impingement angle normally corresponds to erosion of brittle material without any involvement of shear cutting process and thus occurs at high speeds.

The influence of various parameters affecting erosion rate of surface coated materials poses a very complex problem. In general, it is expected that the erosion rate should decrease with increase in hardness and decrease in porosity of the coating (Mishra *et al* 2006). The erosion rate should also decrease with increased involvement of shear process in the surface cutting of target material. In the presence of all these parameters, it is not possible to quantify the influence of individual parameters on the erosion rate. Hence the results obtained in this study do not exhibit any well defined relationship between hardness, porosity and the erosion rate. For example, as seen in figure 4, the stellite-6 coating exhibits maximum erosion damages, even though it possesses maximum hardness. Levy (1988) and Mishra *et al* (2006) have reported that in plasma sprayed coatings, the greater the porosity of the coating, the easier it is for the erodent particles to knock out pieces from the exposed surface, and greater is the removal rate. The porosity thus has an

Figure 7. Scanning electron micrographs of eroded surfaces after 120 min of erosion test at 90° impingement angle of (a) substrate, (b) stellite-6, (c) $\text{Cr}_3\text{C}_2\text{-NiCr}$ and (d) WC-Co-Cr coatings.

overwhelming influence on the erosion behaviour of target material.

3.4 Morphology of eroded surfaces and mechanisms of erosion

Figures 6 and 7 show the scanning electron micrographs of eroded surfaces of substrate material, stellite-6, $\text{Cr}_3\text{C}_2\text{-NiCr}$ and WC-Co-Cr coatings at impingement angles of 30° and 90°, respectively. At 30° impingement angle the process of erosion involves a shear process. Thus the topography of eroded surfaces in the substrate as well as the coatings indicates presence of ploughs, which are formed due to extrusion of platelets from the impact zone (figure 6). The erosion is characterized by intense localized plastic flow producing lips and ploughs around the crater periphery as suggested by Hearley *et al* (1999). Wide ploughs are observed in substrate (figure 6a) and stellite-6 coating (figure 6b), which is indicative of high erosion damages. At 30° impingement angle, cutting due to impinging particle starts in the ductile matrix of stellite-6 around the large M_{23}C_6 carbide grains leading to acceleration in erosion damages. The $\text{Cr}_3\text{C}_2\text{-NiCr}$ and

WC-Co-Cr coatings are continuous and are sufficiently hard to resist cutting due to the impacting erodent particles at 30° impingement angle. This mechanism of erosion of $\text{Cr}_3\text{C}_2\text{-NiCr}$ and WC-Co-Cr coatings is supported by the scanning electron micrographs (figures 6c and d). At 90° impingement angle, the eroded surfaces in all cases are in general free from ploughs (figure 7). Deep craters are instead observed which are created due to dislodging of material by hard hitting erodent particles. The craters as revealed in SEM study are deepest in the stellite-6 coating (figure 7b) in comparison to other coatings. The deep craters observed in the scanning electron micrograph of eroded stellite-6 coating correspond to the removal of large chunks of carbides due to high level of porosity.

4. Conclusions

- (I) The stellite-6 coating on 21-4-N steel substrate exhibits maximum damage due to erosion at 30° and 90° impingement angles. Minimum erosion losses are observed in WC-Co-Cr coating at 30° impingement angle.
- (II) The analysis of the influence of various parameters on erosion behaviour poses a complex problem. It is not

possible to quantify the role of individual parameters like microstructural features, microhardness and porosity in affecting the erosion behaviour of coating. It is, however, observed that the nature and extent of porosity affect to a large extent the erosion rate of coatings. Maximum concentration of porosity is observed in stellite-6 coating.

(III) The erosion damage at 90° impingement angle is more severe in comparison to erosion loss at 30° impingement angle.

(IV) Scanning electron microscopic study reveals that at 30° impingement angle erosion occurs by a shear process involving formation of lips and ploughs on the target surface. Existence of deep craters in the SEM micrographs at 90° impingement angle indicates knocking out of chunk of material from the target surface resulting in high rates of erosion.

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