MICROSTRUCTURAL CHARACTERIZATION AND HOT EROSION BEHAVIOR OF CRC-NICR COATED STEEL USING HVOF TECHNIQUE

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ABSTRACT  
Erosion behavior of the High Velocity Oxygen Fuel (HVOF) deposited CrC-NiCr coating on stainless steel was evaluated. The solid particle erosion study was conducted using an air jet erosion test rig at a velocity 60m/sec and impingement angle 60°, 75° and 90°, on HVOF spray coated steel at 600°C. Microstructure, chemical composition, phases present in the coating on the steel substrate was studied by using Scanning Electron Microscope (SEM) and X-Ray Diffraction method. The Hardness is gradually increasing with increasing content of Cr3C2 particles in all three samples. The erosion mechanism of coatings was also discussed and erosion rate is maximum at impingement angle 75°.

Key words: Chromium carbide, HVOF coatings, Scanning Electron Microscope, Hot erosion, Vickers hardness.

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I. 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. The coal used in Indian power stations has large amounts of ash (about 50%) which contain abrasive mineral species such as hard quartz (up to 15%) which increase the erosion propensity of coal. Pulverized coal, traveling at high velocities through coal burner nozzles and coal nozzle burner tips, typically produces significant component erosion. The burning of coal in thermoelectric power plants generates a huge amount of fly ash that causes intense and localized erosive wear which is the main cause of failure in burner nozzle. In such environments, protective coatings on the surface of stainless steel are used. Mainly coal crusher, coal handling units, coal burner, heat exchanger and fluidized bed combustor (FBC) boilers are the some of the example for hot erosion of metal [2-7]. High velocity oxy-fuel (HVOF) flame spraying has been recognized as the best choice for carbide coatings application [8]. The High Velocity Oxygen Fuel spraying process is expanding its area of coating on hard facing engineering to reduce wear and erosion of metals in the hot erosion components in the field of thermal and nuclear power plants [9-14].

Stainless steel is used as base materials in the present investigation. It has higher strength at elevated temperatures so is often used for structural and pressure-containing applications at temperatures above about 500°C and up to about 800°C. Austenitic Stainless steel contain minimum of 16% chromium and 6% Nickel Chromium Carbide is used as raw materials for coating deposition on stainless steel substrates. Chromium Carbide (Cr$_3$C$_2$) show more complex structure and commonly assigned to minor members of Refractory metals [15]. Chromium carbide was selected as a wonderful protective coating to MMC materials from the standpoint of its capability to resist oxidation (650°C-1200°C) [16], melting point 1850°C [17], high boiling point 3800°C, insoluble in water and its physical compatibility with MMC. This is mainly due to the relatively higher thermal stability and corrosion resistance of Cr$_3$C$_2$ over tungsten carbide which is normally used up to 550°C [18]. Cr$_3$C$_2$–NiCr is very important to be very careful in selecting appropriate proportions coating system as well as correct composition of coating material.

Wang. B et al [19], the relative erosion-corrosion resistances of HVOF Cr$_3$C$_2$–NiCr coating and several other thermal sprayed coatings were determined in an elevated temperature blast nozzle erosion tester. It is found that, in elevated temperature erosion tests involving highly erosive particles, metal, ceramic, and cermet type coatings exhibited characteristics of brittle material erosion behavior, Wastage involved a cracking and chipping mechanism. HVOF Cr$_3$C$_2$-NiCr coating showed excellent erosion-corrosion behavior; the high erosion-corrosion resistance of HVOF Cr$_3$C$_2$-NiCr coating was attributed to its high compactness, fine grain size structure, and a homogeneous distribution of the skeletal network of hard carbides within a ductile, corrosive-resistant metal binder.

Xia et al [20], Cr$_3$C$_2$-NiCr was plasma sprayed on the substrate 1Cr18Ni9Ti in order to solve the erosion wear at high temperature encountered in the oil-refining industry. The erosion-wear test was carried out at room temperature, 400, and 700°C at impact angles of 30° and 90° at a given gas fluid velocity using a high-temperature erosion-wear tester. Plasma sprayed coatings Cr$_3$C$_2$-NiCr improve the erosion resistance of the substrate effectively. Coating Cr$_3$C$_2$-NiCr has good erosion resistance due to its high hardness and moderate toughness. Erosion wear is a systematic period, and every system parameter influences its behavior. Among these
parameters, the hardness and toughness of the target are the most important. A good erosion-resistant target must be tough and hard. The purpose of this investigation is to investigate the hot erosion behavior of Cr$_3$C$_2$-NiCr coated steel specimen by varying NiCr.

2. MATERIALS AND EXPERIMENTAL PROCEDURE

The three different composition of Cr$_3$C$_2$-NiCr powder was used for coating on steel substrate by using HVOF method. Series of Cr$_3$C$_2$-NiCr coated steel specimens of size 75*25*6 mm$^3$ were produced by using HVOF method using 80kW HVOF system. Specimens are initially grit blasted at a pressure of 3 kg/cm$^2$ using Al$_2$O$_3$ having grit size of 60 µm for the average roughness of the surface was 6.8µm. The standoff distance in shot blasting was kept between 120-150 mm. The average roughness of the substrates was 6.8 µm. The grit blasted specimens were cleaned with acetone in an ultrasonic cleaning unit. HVOF process carried out at operating power 80kW and current 550 A. The flow rate of fuel gas was 5.5 liter/minute, oxygen 2.90 liters/minute, spray distance 150 mm and standoff distance is 100 mm. Chemical analysis of base metal was determined by using vacuum emission spectrometer. Carbon of the base metal was analyzed by wet method. Chemical composition of Cr$_3$C$_2$-NiCr powder was analyzed using Energy Dispersive Spectroscopy (EDS). Chemical composition of base metal and Cr$_3$C$_2$-NiCr powder is tabulated in table 2.1 and table 2.2 respectively.

| Table 2.1 Chemical composition of AISI 316 Stainless steel |
|-----------------|----|----|----|----|----|----|----|----|----|
| Grade           | C  | Mn | Si | P  | S  | Cr | Mo | Ni | N  |
| AISI 316        |    |    |    |    |    |    |    |    |    |
| Min             | –  | –  | –  | –  | –  | 16.0 | 2.0 | 10.0 | –  |
| Max             | 0.08 | 2.0 | 1.00 | 0.045 | 0.03 | 18.0 | 3.00 | 14.0 | 0.10 |

| Table 2.2 Compositions of Cr$_3$C$_2$-NiCr Coating samples with Powder size range |
|-------------------------------|-----------------|-----------------|-----------------|
| Coating Samples               | Nominal composition | Powder type | Powder size range (µm) |
| A                             | Cr$_3$C$_2$-20 NiCr | Blend          | 28              |
| B                             | Cr$_3$C$_2$-12 NiCr | Blend          | 28              |
| C                             | Cr$_3$C$_2$-8 NiCr | Blend          | 28              |

Microstructures of the surface coated specimens are taken using Scanning Electron Microscope (SEM) (Zissis) connected to Energy Dispersive X-ray analysis equipments (EDX). Secondary electron detector was used for surface imaging. SEM images were used for study the distribution of Cr$_3$C$_2$ particles on the substrate. XRD pattern was carried out using X-Ray diffract meter with CuK radiation using
wavelength of 1,790 Å at operating voltage 40.0kV and current 30 mA. The 2 range
scanned was 10 to 70 degree at the step size 0.02 degree and count time 0.60 seconds
micro-hardness measurements were made on carbide particles in the surface coating
using ZWICK 3212 micro-hardness tester at a test load of 0.03 kgf and average of
five different readings is computed. Hot erosion tests were carried out using Air Jet
Erosion Tester (TR470-600, DUCOM, and Bangalore) at 600°C using sample
dimensions size 75*25*6 mm³ as per ASTM G76 standard. This test was carried out
by forcing a stream of abrasive (Silica) partials gas through a small nozzle of known
orifice diameter towards the test sample. During the test, abrasive gas stream velocity
maintained at 60 m/s for 10 minutes at known impact angle. Experiments were
reputed for the impact angle 60, 75 and 90 degrees. Erosion of the specimens was
calculated by measuring weight loss of the specimens.

3. RESULTS AND DISCUSSION

![Figure 3.1](image)

**Figure. 3.1 SEM Micrographics of HVOF sprayed chromium carbide coatings
incompositions of Cr3C2-12NiCr**

The chemical composition of the base metal and Cr3C2-NiCr carbides was determined
using vacuum emission spectrometer. The coatings are designated as A, B, and C. All
the coating revealed uniform distribution of Cr3C2-NiCr particles and good bonding
existing between the metal matrix and reinforcements. The above SEM micrographs
of as-sprayed Cr3C2-NiCr coating indicates the formation of the required composition
for HVOF coatings with NiCr metallic binder phase corresponds to the white region
in the micrograph and the dark grey region as the carbides. The microstructures of the
HVOF deposit Cr3C2-20NiCr coatings on steel substrates were studied on the surface
morphology by Scanning Electron Microscope (SEM), from the figure 3.1 (a), (b), (c)
and (d) the coatings has very fine and dense micro structures, Microstructure of the

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coating is highly lamellae with distinct splat boundaries and splats oriented parallel to the substrate surface, due to the deposition and resolidification of molten or semi molten droplets. Also, few pores were detected in the coating, thereby confirming the higher density of the Cr$_3$C$_2$-20NiCr coating. A small amount of unmelted particles can be observed in the microstructures of the coatings.

<table>
<thead>
<tr>
<th>Coating Samples Name</th>
<th>Nominal composition</th>
<th>Hardness HV(0.1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Cr$_3$C$_2$-20NiCr</td>
<td>622</td>
</tr>
<tr>
<td>B</td>
<td>Cr$_3$C$_2$-12NiCr</td>
<td>876</td>
</tr>
<tr>
<td>C</td>
<td>Cr$_3$C$_2$-8NiCr</td>
<td>1065</td>
</tr>
</tbody>
</table>

**Figure 3.2** XRD patterns of Cr$_3$C$_2$-12NiCr sample

The X-ray diffraction patterns of the sample B coating are displayed in Fig. 3.2. A significant peak, characteristic of a substantial amount of elemental chromium (Cr), is observed on the coating. The Cr$_3$C$_2$ major intensities of peaks and limited number of NiCr in the form of Cr$_3$Ni$_2$ peaks are present in the coating. A broad maximum in the range of 42–46 seems to indicate an amorphous phase in the deposit. Cr$_3$C$_2$ was the major phase and binder is the minor phase. A highest peak shows presence of pure chromium Carbide although notable quantity of binder phase is present in the coating.
The measured micro-hardness values of all the three coatings are presented in Fig. 3.3 Micro-hardness measurement is done on these optically distinguishable phases with Vickers micro-hardness Tester using (0.1Hv) load, are summarized in Table 3.1.

![Hardness vs. Coatings](image)

**Figure. 3.3** Hardness vs. Coatings of different Cr$_3$C$_2$-NiCr samples

The average micro hardness of the HVOF thermal sprayed coating is given in the Fig.3.3. The results show that the Cr$_3$C$_2$-NiCr three structurally different phases bear three different ranges of hardness. The Hardness is gradually increasing with increasing content of Cr$_3$C$_2$ particles in all three samples A, B and C. The average micro hardness of the coating is increased with increasing amounts of added chromium carbide in the considered range. The Vickers micro-hardness number of Sample F is high compared to other samples A and B. Sample A composition hardness is low but it has high coating toughness and ductility of the coating because addition of 20% NiCr content to the Cr$_3$C$_2$ coating. The coating toughness and ductility increasing with increasing content of NiCr particles.

Erosion tests were conducted at impingement angles of 60°, 75° and 90° at 600°C using silicon carbide particles as erodent. Erosion rate is gradually increases with increase in impingement angle from 60° to 75° then it is decreases as impingement angle increases and it is concluded that the erosion rate is maximum at impingement angle 75° and minimum at
Microstructural Characterization and Hot Erosion Behavior of CrC-NiCr Coated Steel using HVOF Technique

![Graph](image)

**Figure 3.4** Comparison of Erosion rate vs. different Impingement angles for Compositions of samples A, B and C at 600°C

60° and 90° impingement angles. In general, it is expected that the erosion rate should decrease with increase in hardness and decrease in porosity. A comparison of the morphological features on the eroded surfaces of the high-purity Cr₃C₂-20NiCr Sample subjected to low impact angles 60° and 90° posses low erosion rate than remaining samples. Fig.3.5 (a), (b), (c) and (d) In this micrograph, shows different locations on the worn surface of sample A after erosion by a single dose of 3000 gram of silica erodent particles at an angle of medium impingement of 600. From the figure 3.5 (a) and (b), the micrograph (a) represents the finer nano structure and indentation mark after the work of impingement. The low magnification of micrograph (b) shows presence of Cr2O3 and silica sand. The erodent material quartz silica sand with round circular ball shaped structure and important platelet mechanism sources are observed. Contrarily, smooth surface with shallow pits is observed. The particles get more thermal energy, so during solidification from molten state, they agglomerate to form splats flattened region. Here very less amount of cavitations is observed. It states that, the material is removed in lumps from inter-splat boundaries and deeper groves are observed. Secondary electron micrographs of the region of the elliptical erosion crater that corresponding to particles emerging from near the nozzle wall.
Figure 3.5 Micrographs of Eroded coating A at 75° impingement of Cr$_3$C$_2$-20NiCr

The specimen shows long, narrow grooves at the side of the softer phase fine surface. From the figure 3.5 (c) and (d), A higher magnification view of the central area. The morphology of the surface damage was found to include lips, long narrow groove and wide groove cutting from low erosion incident angle erosion. The groove formation may predominantly occur within the softer binder region and this may also result in undercutting of the carbide grains, which may get loosened and eventually pulled out. The blown up image of the worn region, where there is evidence of primary carbide particle pull out, as shown in figure (d). This impact angles shows regular cut marks (marked sky blue arrow). In this microstructure of impingement angle 60° does not include cracks and pores. The limited amount of oxide content appears in the impact angle surface. As can be seen in Fig. 3.5 (a), when the impingement angle is 60°, the damage occurs by both grain dislodgment and plastic deformation and smearing of the materials.

However, when the impingement angle is increased to 75°, the plastically smeared regions become much smaller and less in number.
4. CONCLUSIONS
The result of the present study Cr$_3$C$_2$-NiCr HVOF coatings can be summarized as follows.

- A comparison of the morphological features on the eroded surfaces of the high-purity 80Cr$_3$C$_2$-20NiCr Sample subjected to low impact angles 60° and 90° possess low erosion rate than remaining samples.
- Chromium carbide as the coating, the erosion wear is maximum at 75° impact angle. Erosion rate is gradually increases with increase in impingement angle from 60° to 75° then it is decreases as impingement angle increases for Cr$_3$C$_2$-NiCr coatings.
- Erosion wear behavior is one of the main requirement of the coatings developed by High Velocity Oxy-Fuel for recommending specific application. In order to achieve tailored erosion wear rate accurately and repeatedly, the influence of the process parameters are to be controlled accordingly. The coating sustains erosion by solid particle impingement substantially and therefore chromium carbide coating considered as a potential coating material suitable for various high temperature thermal power applications such as pulverized coal burner nozzle.

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