Erosion-Corrosion Protection Due to Cr$_3$C$_2$-NiCr Cermet Coating on Stainless Steel

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Abstract: Cr$_3$C$_2$–NiCr coatings have been used extensively to combat the erosion corrosion of hydro power turbine blades made of stainless steel. Cr$_3$C$_2$–NiCr coatings are also used in aqueous corrosive environments due to the high corrosion resistance rendered by the NiCr binder. In this investigation, both erosion and corrosion environments are introduced to cermet coating to study corrosion behavior using potentiodynamic polarization and electrochemical impedance spectroscopy (EIS) techniques. The cermet coatings are useful for reducing the risk of deterioration of mechanical properties of hydro power turbines due to the continuous exposure to the erosive and corrosive action of the corrosive environment containing silt. It was observed that Cr$_3$C$_2$–NiCr coating offered a reasonable improvement in corrosion resistance when compared to bare substrate. The corrosion behavior of the coating was studied in a 150 mL solution of 0.1 M NaCl with 2 gms of quartz particles (0.2–0.8 mm) at various rotation speeds (3000, 4500, 6000 rpm) of the solution over a 1 h immersion using potentiodynamic polarization and EIS studies in a specifically designed experimental set-up for erosion corrosion. When compared to the bare stainless steel samples at 3000 rpm and 6000 rpm, the coating showed the highest improvement at 6.57 times and the least improvement at 3.79 times, respectively.

Keywords: thermal spray; Cr$_3$C$_2$-NiCr; erosion-corrosion; wear; cermet coating; HVOF

1. Introduction

In the field of surface engineering, the structural components subjected to dynamic loading and corrosive environments are protected using various coatings such as super alloy coatings, cermets, nanocomposite hard coatings, etc. with superior tribological and corrosion resistance properties. In hydro power turbine industries, accessories such as pumps, impellers and turbine blades are exposed to aggressive conditions, leading to severe erosion-corrosion causing the shut-down of the plants. Slurry erosion, abrasive wear, erosive wear, cavitation erosion and erosion-corrosion are the main glitches in hydro power turbine systems [1,2]. Therefore, the development of coatings with a significant improvement in erosion-corrosion resistance is critical in avoiding premature failures of components due to erosion-corrosion and the resulting costs and replacement of equipment [3]. In principal, erosion-corrosion is the accelerated degradation of a material or oxide layer on its surface under the combined effect of mechanical erosion and electrochemical attack, whereas erosive wear is caused by the action of sliding, the impact of solids, liquids or gases, or the combination of these. To obviate this problem, High Velocity Oxy-Fuel (HVOF) protective coatings are deposited on turbine alloys [4].
Cr$_3$C$_2$–NiCr and WC-based cermet coatings, obtained by HVOF technique, provide excellent erosion and wear resistance when subjected to the corrosion conditions used in hydro power turbines [5–7]. Though WC-based coatings show a better wear resistance under erosive conditions, their operating temperature is limited to less than 450 °C; however, Cr$_3$C$_2$-based coatings in which chromium carbide particles are embedded in a NiCr metallic matrix can be used in corrosive and moderate wear environments at a temperature of up to 850 °C [8–14]. The formation of the tribo oxide protective film with a low shear strength, which was stable and resistant against a delamination of up to 850 °C during abrasion, accounted for the reduction in the friction coefficient of Cr$_3$C$_2$–NiCr coating, and its higher fracture toughness reduced cracking during surface grinding and tribocorrosion tests [8–14]. The coefficient of friction can be attributed to surface severities and developed internal contact stress, as abrasive particles are in contact with a few asperities [8]. Because of the decrement in contact stress, the area of contact can be increased by increasing the sliding distance [8]. The velocity of the erodent particle affects the erosion of the sample as the erosion damage parameter is directly proportional to the velocity and density of the erodent [8]. The preparation of Cr$_3$C$_2$–NiCr coatings by HVOF technology includes a problem of mechanical carbon loss caused by the rebound of carbide particles hitting the surface [9]. Cermet coatings deposited by thermal spraying have been generally utilized in wear conditions because of their high resistance to abrasion, erosion and high temperatures [10]. The Cr$_3$C$_2$–WC–NiCoCrMo coating shows superior wear resistance as compared with the Cr$_3$C$_2$–NiCr coating at high temperatures (450 °C, 550 °C, 650 °C) [11]. The coating does not show cracks even at higher temperatures (such as 400 °C and more) [9–11]. Electrochemical measurements have shown that Cr$_3$C$_2$–NiCr coatings exhibit a better corrosion resistance when compared to WC–Ni under erosion-corrosion conditions [12]. Cr$_3$C$_2$–NiCr coatings demonstrate a lower wear resistance due to a lower hardness, but their greater fracture toughness reduces coating cracking during surface grinding and tribocorrosion tests [13]. The material losses are much lower in Cr$_3$C$_2$–NiCr coatings when compared to hard chromium coatings, and the corrosion resistance is also comparatively very high [12,13]. Skandan et al. revealed that a multimodal powder (combining coarse and fine particles of WC/Co or coating micron-sized aggregates of WC/Co with a readily diffusible binder) did not appear to undergo significant phase decarburization, showing an improved abrasive and sliding wear resistance [14]. In such multimodal coatings, the nanocrystalline component is likely to melt with relative ease, leading to high-density coating, with coarse particles having only partially melted [14]. Coatings with such multimodal structures are most likely to be hard, ductile and wear-resistant [14].

Several studies report that the Cr$_3$C$_2$–NiCr thermal spray coating possesses a high hardness, low friction coefficient and good corrosion-wear resistance [15–20]. With an increment in the remelting power of 42 kW for Cr$_3$C$_2$-NiCr/NiCrAl coatings on a FV520B steel substrate using plasma arc remelting, the porosity and microcracks of the coating are reduced to a minimum since the NiCr metallic phase is melted and filled into the porosity and microcracks, resulting in an enhancement of the sliding wear resistance [15]. However, an excessive heat input (above 42 kW) increases the sliding wear loss of the coating due to delamination between the bonding layer and steel substrate [15]. The interfacial toughness values were found to increase when increasing the coating thickness [16]. The value of 9.8 MPa.m$^{1/2}$ of the Kca$_0$ parameter for the Cr$_3$C$_2$–NiCr coating deposited by vacuum plasma spray (VPS) is similar in magnitude to those deposited by HVOF [16]. The Cr$_3$C$_2$–NiCr coating made by plasma spraying has a high porosity, and the bonding between the coating and substrate is mechanical [16]. The abrasive wear resistance of Cr$_3$C$_2$–NiCr-coated AA7050-T7 alloy was at least 10 times higher than that of uncoated AA7050-T7 alloy [17]. The Cr$_3$C$_2$–NiCr coating prepared with a higher carrier gas flux showed the highest corrosion resistance in 3.5% NaCl solution, and it is likely that no pitting attack to the substrate occurred even after around 26 h of immersion for the corrosion test [17]. The wear mechanism changes from being abrasive to adhesive in wet conditions when compared to dry conditions [18].

In the Cr$_3$C$_2$–NiCr coating matrix, the NiCr alloy provides corrosion resistance, while the Cr$_3$C$_2$ component acts as a hard phase that assures wear resistance. The corrosion resistance of the Cr$_3$C$_2$–NiCr
coating is due to the NiCr matrix, which allows for an easier and faster repassivation when the coating is subjected to wear [13]. The fine grain structure with a homogeneous distribution of the skeleton network of hard carbide phases provides excellent erosion resistance and is therefore a better alternative to hard oxide coatings [9,11,21–24]. The coatings with better wear resistance and corrosion resistance are used in various environmental conditions, as reported in the literature [5,25–38]. The corrosion and wear resistance of the substrate vary with the angle of impact of erodent particles [29,30]. The Cr$_3$C$_2$–NiCr coatings have always shown a high wear resistance due to a low porosity and high hardness when compared to bare steel or hard chromium coatings [31–34]. The coating made from the high velocity oxy fuel (HVOF) technique has always proven to have a better corrosion and erosion resistance since the technique enhances the uniform distribution of coating particles over the substrate [35–37]. Since the microstructure of coatings determines their erosion and corrosion resistance, it is also better if the coating is made with nanostructured coating particles [38].

The literature on the investigation of the simultaneous erosion-corrosion behavior of Cr$_3$C$_2$–NiCr coating using an electrochemical technique is limited due to the complexity of creating experimental erosion and corrosion conditions. Therefore, the present work has been focused on studying the erosion-corrosion of Cr$_3$C$_2$–NiCr coating using electrochemical techniques. The HVOF was used to fabricate a cermet coating with optimized process parameters. The coated and uncoated SS316 stainless steels exposed to an erosive-corrosive environment are characterized by using X-ray diffraction (XRD) and scanning electron microscopy (SEM) techniques in order to investigate the degradation mechanisms. The electrochemical characteristics of the coatings may be correlated with the microstructural morphologies of the degraded coatings to arrive at better protective measures for stainless steel under actual service conditions.

2. Experimental Method

SS316 stainless steel (obtained from Virwadia Metal & Alloys, Chennai, India) was used as the substrate for the deposition of Cr$_3$C$_2$–NiCr coating. SS316 is named according to AISI 316, and the ASTM standard for this sample is A240. The chemical composition of the SS316 stainless steel used in this study is shown in Table 1.

| Element | Fe | C   | Mn  | P   | S   |
|---------|----|-----|-----|-----|-----|
| wt.%    | Bal.| ≤0.08 | ≤2.00 | ≤0.045 | ≤0.030 |

| Element | Ni | Mo | Si  | Cr  | N   |
|---------|----|----|-----|-----|-----|
| wt.%    | 10–14 | 2.00–3.00 | ≤0.75 | 16–18% | ≤0.10 |

Prior to the spraying process, the samples were degreased with acetone and grid-blasted with Al$_2$O$_3$ (grade 24) using a portable grit blasting machine P7 1000 (which produced the surface roughness) to get a surface with a mean roughness of 5 µm. The surface roughness was measured using a handheld surface roughness meter PCE RT 1200 (PCE Instruments, Southampton Hampshire, UK). The PCE RT 1200 works on the principle of tactile profilometry, according to ISO 3274 [39]. The filters used were high-pass filters, and the instrument also contained an RC filter in it for the prior filtering of noise. The roughness was measured in the Ra parameter. The sampling length was 0.25 mm, and the driving speed during measurement was 0.135 mm/s. The duration of measurement was 1 min. The DJH 2600 type gun HVOF spray technique was used to deposit Cr$_3$C$_2$–25NiCr coatings (the particle size was 45/15 µm) on SS316 (Oxygen flow rate 160–170 lpm, fuel gas flow rate 120–140 lpm, powder feed 80–100 lpm and spray distance 203–254 mm). These parameters ensured the uniform thickness of the coating. The cross-sectional SEM micrographs of the coated specimen were used to measure the average thickness of the coating. The morphology and semiquantitative chemical analysis of the coatings were performed by Quanta 400 FEG SEM (FEI company, Hillsboro, OR, USA) operating at a 9.2 mm or 11.1
mm working distance and 20 kV voltage and by X-ray energy dispersive spectroscopy (EDS). For the structural analysis, all the samples were characterized by X-ray diffraction (XRD) (Bruker D8 Discover instrument, Billerica, MA, USA) with an Cu-Kα radiation from 20 to 90 degree at a scan rate of 1 degree per minute with a step size of 0.0149 degrees.

**Erosion-Corrosion Test**

The erosion-corrosion tests were performed in a 150 mL solution of 0.1 M NaCl solution with 2 gms of quartz particles (0.2–0.8 mm) at various rotation speeds for a 1 h immersion using potentiodynamic polarization and EIS studies in a specifically designed experimental set-up for erosion-corrosion in aerated conditions (Figure 1a,b).

![Figure 1. (a) Erosion-corrosion test set-up (b) erosion-corrosion chamber, (c) schematic diagram of the sample holder for the erosion-corrosion test.](image)

The sample was tested using a sample holder whose schematic is given Figure 1c. Figure 2 shows a photograph of the erosion-corrosion test set-up and a photograph of the erosion-corrosion chamber.

![Figure 2. Photograph of the erosion-corrosion test set-up and photograph of the erosion corrosion chamber.](image)

The abrasive solution of NaCl + SiO₂ was driven by a rotating shaft, GAMRY RDE710 (Gamry Instruments, Warminster, PA, USA), used as agitator impeller and rotating at a constant rate of 3000, 4500 and 6000 rpm, respectively. The coated and uncoated steel samples were subjected to an open circuit potential test in erosive-corrosive conditions for 1 h before conducting electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization studies. EIS and potentiodynamic polarization measurements were made using coated steel samples as working electrodes, a saturated calomel electrode as the reference and a platinum wire as a counter electrode. EIS measurements were performed at an open circuit potential (OCP) using a frequency range of 0.01 Hz to 100 kHz. Open circuit potential (OCP) and electrochemical impedance (EIS) measurements were done using GAMRY reference...
600+ Potentiostat/Galvanostat/ZRA (Gamry Instruments, Warminster, PA, USA). The sample was exposed at an area of 1 cm². Potentiodynamic polarization curves were obtained from −300 mV to +400 mV versus \( E_{ocp} \) (open circuit potential) at a scan rate of 0.1667 mV s⁻¹ (ASTM F2129-04) [40]. All electrochemical experiments were performed at room temperature (25 °C). The obtained data were analyzed using software GAMRY Echem analyst version 7.06 (Gamry Instruments, Warminster, PA, USA).

3. Results and Discussion

3.1. Characterization of Coating

Figure 3 shows the X-ray diffraction peaks of the Cr₃C₂–NiCr-coated sample before corrosion. All coating samples, including Cr₃C₂, NiCr, Cr₇C₃, Cr₂₃C₆, Ni and Cr, have shown the following phase composition. At high temperatures and an oxidizing atmosphere, several reactions could occur leading to the decomposition of the original phases, thereby forming new phases during the spraying process [15,17]:

\[
\begin{align*}
7\text{Cr₃C₂} & \rightarrow 3\text{Cr₇C₃} + 5\text{C} \\
14\text{Cr₃C₂} + 5\text{O}_2 & \rightarrow 6\text{Cr₇C₃} + 10\text{CO} \\
23\text{Cr₃C₂} + 14\text{O}_2 & \rightarrow 3\text{Cr₂₃C₆} + 28\text{CO}
\end{align*}
\]

![X-ray diffraction pattern of the Cr₃C₂–NiCr coated sample.](image-url)

The surface morphology of the Cr₃C₂–25NiCr coating is shown in Figure 4 at different magnifications. The microstructure of the coating consists of the initial microstructure (larger spherical hard phase, dark grey) embedded in binder (bright light grey). It can be inferred that the coating has uniform and dense microstructures and exhibits layered morphologies due to the deposition and resolidification of molten or semimolten droplets. The surface SEM of the coating also indicates the presence of melted, partially melted and unmelted particles, which are identified in the coating by their size and surface morphology. However, only a limited number of unmelted particles can be observed in the microstructures. The coating also possesses some voids and cracks that are typical characteristics of the HVOF-sprayed coating. The dark phase contains a higher amount of Cr than the bright phase. The coating microstructure consists of metallic binder that is NiCr-rich (light grey area) and Cr₃C₂-rich
(dark grey area). The cross-sectional SEM micrographs of the coated specimen are used to measure the average thickness of the coating, as shown in Figure 5. The coating thickness is 200 ± 20 µm (Figure 5).

![SEM micrographs of the coated specimen](image)

**Figure 4.** Surface morphology of the Cr$_3$C$_2$–25NiCr coating at: (a) Lower magnification, (b) intermediate magnification and (c) higher magnification; (d) Surface profile of the coating with EDS spectra.

### 3.2. Erosion-Corrosion Behavior

To investigate the corrosion behavior of Cr$_3$C$_2$–NiCr-coated and uncoated stainless steel in a 150 mL solution of 0.1 M NaCl solution with 2 gms quartz particles (0.2–0.8 mm) at various rotation speeds using potentiodynamic polarization and EIS studies in a specifically designed experimental set-up for erosion-corrosion in aerated conditions, $E_{corr}$ (corrosion potential) versus time plots were generated after immersion in a 150 mL solution of 0.1 M NaCl solution with 2 gms quartz particles (0.2–0.8 mm) at various rotation speeds, in order to ascertain the stabilized open circuit potential (OCP). When the fluctuation for OCP is limited to <10 mV for a period of 1000 s, the condition is considered stable for conducting EIS experiments. The OCP tests were performed for 1 h before conducting the erosion-corrosion tests (EIS and potentiodynamic polarization tests) for uncoated and Cr$_3$C$_2$–NiCr-coated stainless steel samples in a slurry containing a 150 mL solution of 0.1 M NaCl solution with 2 gms quartz particles (0.2–0.8 mm) rotating at a constant rate of 3000, 4500 and 6000 rpm, respectively.
Figure 5. Cross-sectional images of the coating at different magnifications to determine the coating Table (a) 100×, (b) 600×, (c) 300×; and (d) cross-sectional image with EDS spectra.

Figure 6 shows the Bode impedance plots for the various speeds of the rotating shaft. The magnitude of impedance at the lowest frequency is a broad measure of corrosion resistance if reaching the asymptotic limit at the lowest frequency. The corrosion resistance improvement gradually decreases as the rotation speed increases, clearly showing that as the speed of rotation increases, the silt particles’ impact over the coating also increases, which leads to a higher erosion factor. The number of peaks in the Bode phase plot equals the number of time constants (Figure 7). The diameter of the semicircle of a Nyquist plot is a broad measure of corrosion resistance. The Nyquist plot shown in Figure 8 proves the corrosion resistance resulting from the coating through the variation in the shape of the curves and the respective Zreal and Zimg values. Since the Nyquist plots in Figure 8
are not perfect semicircles and do not complete the semicircles, we can only obtain a qualitative analysis for the corrosion resistance. Since there is a one-time constant in the equivalent circuit, as shown in Figure 9, only one peak in the Bode phase plot is shown in Figure 7. It is observed that $n$, $Z_{cpe}$ and $R_{ct}$ (as calculated in Table 2) have a significant effect on the phase angle at low frequencies; meanwhile, at high frequencies, the change in $R_{ct}$ has no significant effect on the phase angle [41]. Furthermore, the peak angle for the coated samples is shifted towards a lower frequency region when compared to the uncoated samples. This may be due to the accumulation of more corrosion products for the uncoated samples when compared to the coated samples. The one-time constant is attributed to the presence of the Cr$_3$C$_2$–NiCr coating/solution interface in the case of the Cr$_3$C$_2$–NiCr-coated stainless steel samples, while the one-time constant is due to the development of metal hydroxide/oxide films, i.e., corrosion products/solution interface, in the case of the bare stainless steel sample.

![Figure 6. Comparison of the Bode impedance plots of the Cr$_3$C$_2$–NiCr-coated and uncoated SS316 samples at different rotation speeds.](image)

![Figure 7. Bode phase plots for the Cr$_3$C$_2$–NiCr-coated and uncoated SS316 samples at different rotation speeds.](image)
The equivalent circuit model used for EIS modelling is shown in Figure 9 [42]. The circuit consists of the solution resistance (Rs), charge transfer resistance between the coatings and solution (Rct), and coating double-layer capacitance (CdI) expressed by a constant phase element (Z_{CPE}). One capacitive loop is found in the obtained EIS results, since the coating that was made was a single layer coating due to the formation of corrosion products over the coating layer. The coated stainless
Steel samples have shown a better improvement when compared to the uncoated samples since the coating showed the formation of corrosion products, as discussed in the Table 2.

Table 2 reveals that the corrosion resistance (i.e., charge transfer resistance between the coating and solution) of Cr2C2–NiCr-coated stainless steel is $20.52 \times 10^3 \, \Omega \cdot \text{cm}^2$, $34.08 \times 10^3 \, \Omega \cdot \text{cm}^2$ and $22.0 \times 10^3 \, \Omega \cdot \text{cm}^2$ for 3000, 4500 and 6000 rpm, respectively, and that that of uncoated stainless steel is $3.12 \times 10^3 \, \Omega \cdot \text{cm}^2$, $6.232 \times 10^3 \, \Omega \cdot \text{cm}^2$ and $5.792 \times 10^3 \, \Omega \cdot \text{cm}^2$ for 3000, 4500 and 6000 rpm, respectively. The corrosion resistance of the Cr2C2–NiCr-coated SS316 substrate was improved by 6.57 times when compared to the uncoated SS316 substrate at 3000 rpm, whereas at 4500 rpm it was reduced by up to 5.47 times due to the erosive action of the silt (Table 2, as obtained from EIS modelling). Although the corrosion resistance of the coating decreased at 6000 rpm, there was an improvement of about 3.79 times when compared to the bare substrate (Table 2). This is attributed to the formation of a protective layer that allows for rapid passivation and repassivation during erosion.

Generally, in Bode impedance plots, the impedance at the lowest frequency is considered as corrosion resistance and should match with the values obtained for corrosion resistance by EIS modelling if the impedance values at the lowest frequency reach asymptotic limits. In our study, we can clearly see in Figure 6 that, in the Bode impedance plot for the coated samples (3000, 4500, 6000 rpm), the values for impedance at the lowest frequency do not reach asymptotic limits; therefore, it is not advisable to compare the values of impedance at the lowest frequency with those obtained for corrosion resistance by EIS modelling. However, this is not the case for the uncoated samples. For all three conditions (3000 rpm, 4500 rpm and 6000 rpm), the values of impedance at the lowest frequency reach an asymptotic limit, and they are compared with those obtained by EIS modelling in Table 2.

The coating exhibits a better performance due to the formation of corrosion products (Cr2O3). However, in the case of erosion-corrosion, the scenario differs due to the erosive action of silt particles. Furthermore, there is a dual effect of erosion and corrosion that affects the coating performance immensely. The corrosion resistance in terms of impedance is shown in Figure 6, and it is reported that the coated samples perform well towards the erosion-corrosion environment when compared to the uncoated samples. The improvement in the corrosion resistance offered by the coating decreases with an increase in the rotational speed due to the more severe erosion action of silt particles.

The erosion-corrosion behavior of the coated and uncoated stainless steel samples was further explored by potentiodynamic polarization studies for various rotation speeds (Figure 10). There is a positive shift in $E_{corr}$ and a negative shift in $I_{corr}$ for the coated samples when compared to the uncoated samples, demonstrating an improvement in the corrosion resistance (Table 3). The coated sample with low speed rotations shows a far better corrosion resistance performance when compared to the uncoated sample. On the other hand, when the speed of rotation increases, the effect of erosion increases for the sample when compared to corrosion, thereby leading to a gradual decrease in the resistance of the coating [35]. Furthermore, other mechanical properties, like porosity, hardness, etc., also play a major role in determining the erosion-corrosion resistance of the material. The corrosion resistance of the coating is mainly due to the binding phase of NiCr itself, to less porosity and to there being very few microcracks, as well as to the formation of protective post-corrosion products, such as those observed in the present work.

Table 3 show the erosion corrosion behavior of the coated and uncoated samples in terms of the corrosion rate. The values of the corrosion rate are directly related to the corrosion current $I_{corr}$. The calculations of the equivalent weight and corrosion rate were made by using the ASTM Standard G 102 [43]. The $I_{corr}$ values for the coated samples and uncoated samples were obtained using Tafel plots on potentiodynamic polarization curves. The $I_{corr}$ value obtained from the potentiodynamic polarization curve for the coated stainless steel sample was found to be 6.72 times lower than that obtained for the uncoated sample for a 3000 rpm rotation speed of the solution, which was consistent with the results obtained from the EIS modelling. This shows a 6.57-fold improvement of the corrosion resistance for the coated sample when compared to the uncoated stainless steel sample for a 3000 rpm rotation speed. Similarly, the $I_{corr}$ value obtained from the potentiodynamic polarization curve for

| rpm | Coated Sample | Uncoated Sample |
|-----|---------------|-----------------|
| 3000 | 4.232 \times 10^{-2} \, \text{mA/cm}^2 | 5.792 \times 10^{-2} \, \text{mA/cm}^2 |
| 4500 | 2.842 \times 10^{-2} \, \text{mA/cm}^2 | 4.682 \times 10^{-2} \, \text{mA/cm}^2 |
| 6000 | 1.712 \times 10^{-2} \, \text{mA/cm}^2 | 2.832 \times 10^{-2} \, \text{mA/cm}^2 |
the coated sample for 4500 rpm was found to be 5.32 times lower than that obtained for the uncoated sample for 4500 rpm, which was consistent with the EIS results showing a 5.47-fold improvement in the corrosion resistance for the coated sample when compared to the uncoated sample for 4500 rpm. It is further observed that the $I_{corr}$ value obtained from the potentiodynamic polarization curve for the coated sample for 6000 rpm was found to be 3.76 time lower than that obtained for the uncoated sample for 6000 rpm, which was consistent with the EIS result showing a 3.79-fold improvement in the corrosion resistance for the coated sample when compared to the uncoated sample. Therefore, the results obtained from the potentiodynamic polarization test are in agreement with the EIS results.

![Comparison of potentiodynamic polarization curves at various rotational speeds of erosion corrosion particles.](image)

**Figure 10.** Comparison of potentiodynamic polarization curves at various rotational speeds of erosion corrosion particles.

**Table 3.** Electrochemical values of the uncoated SS316 and coated samples in 0.1 M NaCl at 25 °C.

| Rotation Speed (rpm) | Sample   | $E_{corr}$ (mV) | $I_{corr}$ (µA) | Corrosion Rate (mpy) |
|----------------------|----------|-----------------|-----------------|---------------------|
| 3000                 | Uncoated | −336            | 5.37            | 2.126               |
|                      | Coated   | −177            | 0.798           | 0.316               |
| 4500                 | Uncoated | −154            | 0.926           | 0.336               |
|                      | Coated   | −137            | 0.174           | 0.068               |
| 6000                 | Uncoated | −180            | 1.03            | 0.408               |
|                      | Coated   | −145            | 0.274           | 0.108               |

The Cr$_3$C$_2$–NiCr-coated samples have shown a significant improvement in the corrosion resistance when compared to the uncoated samples.

The present research is based upon electrochemical corrosion studies of Cr$_3$C$_2$–NiCr coating in the presence of an erosive environment, i.e., the suspension of silica particles in the electrolyte solution. Therefore, the authors have limited the scope of the erosion studies to electrochemical corrosion studies only, and further research on mass and thickness loss measurements may be done in future research.

### 3.3. Post-Corrosion Morphology

The post-corrosion morphology of Cr$_3$C$_2$–25NiCr-coated samples was studied using XRD and SEM techniques. The typical phases observed in XRD are Cr$_3$C$_2$, NiCr, Cr$_{23}$C$_6$, Cr$_7$C$_3$, CrO$_2$, Cr$_2$O$_3$ and NiCr$_2$O$_4$ (Figure 11). Although the X-ray peaks show the same peaks as before erosion-corrosion,
Cr$_2$O$_3$, CrO$_2$, and NiCr$_2$O$_4$ peaks with a relatively lower intensity are observed in the X-ray diffraction patterns when compared to the corresponding peaks in the coating [24,44]. It is well established that a very small amount of Cr$_2$O$_3$ is always present in the coating since it is deposited using a thermal spray coating technique like HVOF; therefore, the possibility of oxidation is expected in the deposition process itself but in little amounts. The intensity of Cr$_2$O$_3$ peaks increased after the erosion-corrosion process when compared to before erosion-corrosion, from which one can conclude that the coating underwent corrosion. The passive layer that was formed showed the formation of Cr$_2$O$_3$ but also CrO$_2$, which could alter the mechanical properties of the coating [42].

![X-ray diffraction pattern of the Cr$_3$C$_2$–NiCr-coated sample after erosion-corrosion.](image)

Figure 11. X-ray diffraction pattern of the Cr$_3$C$_2$–NiCr-coated sample after erosion-corrosion.

Figure 12 shows the surface morphology of the Cr$_3$C$_2$–25NiCr coating after erosion-corrosion at different rotating speeds. In terms of the coating, when it is subjected to a lower speed of rotation (i.e., 3000 rpm), the silt particles do not possess a greater centripetal force, as a result of which the impact over the surface is lower and the corrosion factor mainly takes place over the coating. When the speed is increased, the silt particles gather more force, as a result of which the impact on the coating is higher and the erosion plays a more major part than the corrosion, limiting the formation of fewer corrosion products on the surface of the coating layer [42,45]. The SEM images show the morphology, showing the major role of erosion at a higher rotational speed when compared to corrosion. EDS was conducted in order to confirm the post-corrosion products on the coatings (Figure 13). The formation of micro pores was observed over the surface of the coating, accelerating the corrosion process, but since there were NiCr binder elements present in the coating, the effect of the corrosion was limited by the coating, adding a further corrosion resistance to the coating. Fewer microcracks were also found in the coating, which was due to the fact that an instantaneous erosion-corrosion process took place, but the cracks still did not actively participate in the erosion-corrosion process on the coating.
showing the major role of erosion at a higher rotational speed when compared to corrosion. EDS was conducted in order to confirm the post‐corrosion products on the coatings (Figure 13). The formation of micropores was observed over the surface of the coating, accelerating the corrosion process, but since there were NiCr binder elements present in the coating, the effect of the corrosion was limited by the coating, adding a further corrosion resistance to the coating. Fewer microcracks were also found in the coating, which was due to the fact that an instantaneous erosion‐corrosion process took place, but the cracks still did not actively participate in the erosion‐corrosion process on the coating.

Figure 12. Surface morphology of the Cr$_3$C$_2$–25NiCr coating after erosion‐corrosion at different rotating speeds of (a) 3000, (b) 4500 and (c) 6000 rpm.

Figure 13 shows the Cr rich with Ni and O elements present in the microstructure. Pores and micropores are present as similar to the microstructure before the electrochemical corrosion test. No indication of pitting and the iron oxide layer was observed in the Cr$_3$C$_2$–NiCr‐coated samples after the corrosion test. As compared to the uncoated Cr$_3$C$_2$–NiCr, the coated samples were found to exhibit a corrosion resistance attributed to the presence of a protective NiCr metallic binder and fine grain structure with a homogeneous distribution of a skeleton network of hard carbide phases. The EDS showed an oxygen content in the coating after erosion‐corrosion, and the XRD peaks also supported that the corrosion products were Cr$_2$O$_3$ and CrO$_2$. 

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Figure 12. Surface morphology of the Cr$_3$C$_2$–25NiCr coating after erosion‐corrosion at different rotating speeds of (a) 3000, (b) 4500 and (c) 6000 rpm.
Figure 13. Surface morphology and EDS spectrum of Cr$_3$C$_2$–25NiCr coating that is (a) Ni-rich and (b) O$_2$-rich after electrochemical erosion-corrosion in 0.1 M NaCl solution at two different magnifications.

4. Conclusions

The electrochemical erosion-corrosion behavior of Cr$_3$C$_2$–NiCr coating was investigated in the present work. The coating was deposited over a stainless steel SS316 substrate using the HVOF technique. The following conclusions are made based on the present study:

A. The Cr$_3$C$_2$–NiCr-coated stainless steel shows a better resistance against the erosion and corrosion environment when compared to bare stainless steel. The coating withstands the impact of silica particles in a corrosive environment.

B. The relative improvement in the corrosion resistance decreases when the rotation speed is increased due to the more severe erosion action of SiO$_2$ particles.

C. The post-corrosion products add a better corrosion resistance to the coating layer, which is why the cermet coatings are more corrosion resistant than most of the bare alloys.

D. Electrochemical impedance spectroscopy provides a quantitative estimation of the corrosion rate of the coatings. The improvement in the corrosion resistance of the Cr$_3$C$_2$–NiCr coating at 3000 rpm was found to be about 6.57-fold (557% increment in corrosion resistance), whereas at 4500 rpm it decreased to 5.47-fold (447% increment in corrosion resistance) and at 6000 rpm
it was reduced to 3.79-fold (279% increment in corrosion resistance) when compared to a bare stainless steel sample at the respective rpm speeds.

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