Performance analysis of erosion resistant Mo$_2$C reinforced WC-CoCr coating for pump impeller with Taguchi’s method

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Abstract

Purpose – This study aims to deal with development and performance analysis of high-velocity oxy-fuel (HVOF) thermally sprayed Mo$_2$C-based WC-CoCr (tungsten carbine cobalt chrome) (Co-10% and Cr-4%) cermet coating deposited on the pump impeller steel 316 L.

Design/methodology/approach – In this work, a study was carried out by modifying the conventional WC-CoCr powder with a small addition of molybdenum carbide (Mo$_2$C). Reinforcement was done by 1–4 wt.% addition of Mo$_2$C feedstocks in WC-CoCr powder by using a jar ball mill process. The design of experiment was implemented for optimization of the percentage of Mo$_2$C feedstock. L16 (4$^4$/C$^2$4) orthogonal array was used to design the experiments for erosion output for the input parameters namely velocity, particle size, concentration and Mo$_2$C proportion.

Findings – Results show that the Mo$_2$C-based WC-CoCr coating provides better microhardness as compared to conventional WC-CoCr coating. The present study also reveals that the deposition of conventional WC-CoCr coating has improved the wear resistance of SS 316 L by 9.98%. However, the slurry erosion performance of conventional WC-CoCr coating was improved as 69.6% by the addition of 3% Mo$_2$C.

Practical implications – WC-CoCr coatings are universally used for protecting the equipment and machinery from abrasion, erosion and corrosion. So, the 3% Mo$_2$C-based WC-CoCr can be useful in power plants and various industries like mining, chemical, automobile, cementing and food processing industries.

Originality/value – A new HVOF coating has been developed by the addition of Mo$_2$C feedstock in WC-CoCr powder (Co 10% and Cr 4%) and the percentage of Mo$_2$C feedstock was optimized to improve the tribological behavior of WC-CoCr coating.

Keywords Slurry, Solid particle erosion, High-velocity oxy-fuel technique, Taguchi 2019s method

Paper type Research paper

1. Introduction

Nowadays, almost every engineering field is facing the problem of protecting the machinery from different types of damage or failures. Slurry erosion (SE) is a complex and unavoidable phenomenon which involves the interaction between solid particles immersed in a fluid and a target surface (Szala and Łukasik, 2016; Al-Bukhaiti et al., 2018; Shibe and Chawla, 2019; Singh, 2019; Singh et al., 2019b). This phenomenon raises significant issues like failure of components, high maintenance cost and low efficiency in various industrial sectors such as hydro/thermal power plants, mining and chemical industry (Singh et al., 2018, 2019b). Therefore, a variety of components installed in different industries are covered with hard coatings to protect them against erosion damage.

High-velocity oxy-fuel (HVOF) thermal spray coatings are widely used for this purpose (Thakur et al., 2011). Amongst the materials, WC-CoCr cermet coatings offer low porosity, high microhardness, toughness and corrosion resistance. WC-10Co4Cr coating is frequently used in various industries for the protection of steel against oxidation, corrosion and abrasion (Cui et al., 2017). A detailed literature survey was done, reviewing earlier analyses of the mechanical, microstructural and tribological properties of WC-CoCr (tungsten carbine cobalt chrome) coatings undertaken by different researchers. Researchers (Thakur et al., 2011) reported that the formation of craters was suppressed with the presence of WC grain, which indeed reduce the SE. Numerous researchers also used different ductile and brittle materials like TiO$_2$, ceramics, nano-sized powders, carbon nanotubes, etc., to enhance the mechanical and surface properties of hard coatings (Liu et al., 2010; Thakur et al., 2011; Vernhes et al., 2016). The inclusion of various elements in WC-Co-Cr coating may be useful for the improvement of the specific properties such as hardness, toughness, durability, stiffness,

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elongation, ductility, porosity, additional phase composition and so on (Berger, 2015).

Additionally, the introduction of several feedstocks allows for enhancing the specific WC-CoCr coating properties. MoS₂ was previously used as a lubricant for various materials for resistance against dry erosion (Vazirisereshk et al., 2019; Rosenkranz et al., 2021). However, the Mo₂C is an ideal alternative among other materials owing to the properties of carbon lubrication and other properties such as chemical durability, microhardness, strength and tolerance to oxidation at elevated temperatures. Recently, Singh et al. (2019a) developed 3% Mo₂C-based WC-Co-Cr coating powder and tested the erosion and corrosion by using the pot tester. They tested the erosion wear of conventional powder was increased by addition of Mo₂C powder. However, the effect of particle size which plays crucially in erosion wear remained unstudied. Thus, the present study aims to study the influencing parameters that play crucially in erosion wear of traditional and Mo₂C-based WC-CoCr coating using Taguchi’s method.

2. Materials and methodology

2.1 Substrate material
Substrate material, i.e. impeller steel SS 316L was procured from Pearl Overseas, Mumbai (Maharashtra, India). The nominal composition of substrate materials was tested using optical emission spectroscopy with Foundry master spectrometer (Manufacturer: Oxford Instruments, Uedem, Germany). The results of the nominal composition are listed in Table 1. The dimensions of the test specimen were taken as 67.5 × 25.4 × 5.0 mm with a circular hole of radius 4 mm at the center.

2.2 Coating powders
Commercial WC-CoCr (tungsten carbine cobalt chrome) (WOKA 3533: 10% Co and 4% Cr) cermet powder (average particle size: 45 ± 15 µm) was used as thermal spraying powder which was purchased from Parshwamani Metals, Mumbai (India). Figure 1(a, b) shows the scanning electron microscopy (SEM) images of thermal spraying powders at a magnification of 1000×. Reinforcement of Mo₂C feedstocks in WC-CoCr powder was done by using a jar ball mill process with surface hardened steel balls. The optimized time of 8 h was taken for the ball milling. The percentage of Mo₂C is taken below 4%. The increased percentage of carbon causes formation of cementite (Fe₃C) with steel surface at high plasma, i.e. 1150–1394°C. This is not desired for good coating adherence. The flowability of powder was tested by calculating the angle of repose method (ASTM C1444-00, 2000). The angle of repose of 1%, 2%, 3% and 4% composition was found as 26.73°±1.5°, 30.6°±1.5°, 56.1°±1.5° and 41.6°±1.5°, respectively. Finally, the 3% Mo₂C-based powder was prepared with spherical microstructure in reduced size as compared to conventional WC-CoCr powder, as seen in SEM image [Figure 1(c)].

2.3 High-velocity oxy-fuel technique
Before spraying, the substrates were degreased and sandblasted with 30 mesh quartz particles to enhance the adhesive strength. The roughness (Rff) of SS316L prior and after sandblasting was measured as 0.086 ± 3% and 8.23±5% µm, respectively. The HVOF spraying was carried out by using a commercial MP-2100 thermal spraying system using nitrogen as fuel gas and argon as a carrier gas. The specifications of the MP-2100 thermal spraying unit are listed in Table 2. The coating parameters were chosen from the previous study (Singh et al., 2019c).

2.4 Materials characterization
The crystalline phases of coatings were identified by X-ray diffractometry (XRD: X’Pert, Philips, The Netherlands) for reference Cu Kα (λ = 1.54 Å). The electron beams were generated at a voltage of 40 kV and a current 30 mA. During XRD analysis, the step angle was varied as 0.01° for the Bragg’s angle range of 10°–80°. The microstructural analysis was carried out using SEM (JEOL 6510LV, The Netherlands). The insulating materials were made conducting by performing the gold sputtering using auto fine coater (JFC-1600 JEOL, The Netherlands) to facilitate them conduction behavior. An image analysis technique was used to obtain 2D and 3D surface profiles with the help of MountainsLab 8.0 (DigitalSurf, 2020). The value of roughness for coatings was measured by using roughness tester (SurfTest, SJS-400 Mitutoyo, USA). Microhardness tests were performed by using Vicker’s tester (MVH-1, Metatech Pune, India) six times for each sample by taking a load of 9.8 N and dwell time of 20 s. The coating porosity was measured by using the water immersion method (Melnik and Skeet, 1986). The fracture toughness of coating was measured by using the following correlation by Niihara (1983):

\[
K_c = 0.0711 \times \left( \frac{Hv}{\sqrt{d}} \right) \times \left( \frac{E}{Hv} \right) \times \frac{[c]}{[d]}^{1.7} \tag{1}
\]

In above equation, the Hv is the Vickers’s microhardness, and E is the elastic modulus. However, c is calculated by the following equation:

\[
c = \frac{(2d_{\parallel} + d_{\perp})}{4} \times \left( \frac{a_1 + a_2}{2} \right) \tag{2}
\]

In equation (2), the \(d_{\parallel}\) and \(d_{\perp}\) are the parallel and perpendicular diagonal lengths of Vickers’s indents, respectively.

| Table 1 | Nominal chemical composition (wt.%) of pump impeller steel SS 316L |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Materials       | S               | P               | C               | Mo              | Mn              | Si              | Ni              | Cr              | Co              | Fe              |                  |
| Measured wt.%   | 0.005           | 0.043           | 0.005           | 1.69            | 1.020           | 0.135           | 10.350          | 16.600          | 1.690           | Balance         |                  |
| Actual wt.%     | Min             | –               | –               | 2.0             | –               | –               | 10.0            | 16.0            | –               | Balance         |                  |
|                  | Max             | 0.03            | 0.045           | 0.03            | 3.0             | 2.0             | 0.75            | 14.0            | 18.0            | 2.0             | Balance         |
Figure 1 SEM-EDS of (a) WC-10Co4Cr, (b) Mo2C, (c) newly developed 3% Mo2C + WC-10Co4Cr and (d) sand particles

Table 2 Details of different parameters and equipments

<table>
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<th>Spray parameter</th>
<th>Flow rate</th>
<th>Pressure</th>
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<td></td>
<td></td>
</tr>
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<td>Compressed air</td>
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<td>2</td>
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<td>3</td>
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<td></td>
<td></td>
</tr>
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<td>HVOF spraying</td>
</tr>
<tr>
<td>2</td>
<td>Powder feeder</td>
<td>PF-3350-HP</td>
<td>Feeding powder in spraying gun</td>
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<tr>
<td>3</td>
<td>Rotameter type gas metering system</td>
<td>FR-2100 unit</td>
<td>To regulate the air flow</td>
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<table>
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<tr>
<td></td>
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<td>V₂ = 2.71</td>
<td>V₃ = 3.61</td>
<td>V₄ = 4.59</td>
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<td>C₂ = 40</td>
<td>C₃ = 50</td>
<td>C₄ = 60</td>
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<tr>
<td></td>
<td>Particle size (µm)</td>
<td>d₁ = 45.6</td>
<td>d₂ = 93.4</td>
<td>d₃ = 121.7</td>
<td>d₄ = 257.8</td>
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<td></td>
<td>Mo₂C addition (wt.%)</td>
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<td>M₂ = 2</td>
<td>M₃ = 3</td>
<td>M₄ = 4</td>
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Mo₂C reinforced WC-CoCr coating
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3. Taguchi’s orthogonal array

A pot tester was used for the SE experimentation purpose. Jet-impingement test method is standard method to evaluate the erosion wear due to gas-solid flow, as recommended by ASTM-G76-95 (2000). However, slurry pot tester was recommended by Desale et al. (2005) for the evaluation of erosion wear by solid-liquid slurry in pump and pipelines. Firstly, the weight loss from specimen was measured by using a digital weight balance. The density of coating was measured by conventional gravimetric method as follows:

\[ t = \frac{m}{A \times \rho} \]  

(3)

where \( t \) is the film thickness (\( \mu m \)), \( m \) is the mass (g), \( \rho \) is the density (g/m\(^3\)) and \( A \) is area of specimen covered (m). The mass of specimen was measured by taking the difference of bare and coated specimen. Thus, the coating density of 1, 2, 3 and 4 wt. % Mo\(_2\)C reinforced WC-CoCr was measured as 16.83, 15.85, 14.22 and 13.16 gm/m\(^3\) (deviation: ±4.5%), respectively. Volume loss was calculated by using the fundamental relation between density, mass and volume. In the present work, the Taguchi’s method was applied to identify the most influencing parameter, reduce the experimentation time and cost (Taguchi, 1990). The details of the input parameters are listed in Table 2 (c). L\(_{16}\) (4 \( \times \) 4) orthogonal array was used to design the experiments for SE output (i.e. weight loss in g). A set of experiments for the different input parameters is tabulated in Table 3. In the present study, MINITAB 18 software was used to obtain the signal-to-noise (S/N) ratios, i.e. a factor minimizing the noise and correcting the value of inputs. The S/N ratio was calculated by taking lower-the-better quality rule, as follows:

\[ \frac{S}{N} = -10 \times \log \left[ \frac{1}{n} \sum E_i^2 \right] \]  

(4)

In equation (1), \( E \) is the SE observations and \( n \) is the total observations.

4. Experiments

The experiments were carried out to produce the SE by using a rotating type pot tester (TR41, Ducom tester, Ducom Instruments, The Netherlands), as shown in Figure 2. This tester consists of components like a base plate (530 \( \times \) 530 \( \times \) 15 mm), slurry vessel size (\( \varphi \) 120 and 120 mm depth), cooling tank (190 \( \times \) 140 mm), water inlet and output pot size (3/4 in. hose pipe) and controller of power supply (230 V \( \times \) 50 Hz, current rating of 5 Amp and power rating of 0.4 kW). River-side sand was used to prepare the slurry. SEM-EDS images of sand are shown in Figure 1(d). EDS maps show the presence of O, Na, Mg, Al, Si, K and Fe as 52.46%, 0.35%, 0.55%, 2.55%, 39.38%, 1.46% and 3.25%, respectively. British standard sieves were used to examine the weighted mean diameter (\( d_{\text{wmd}} \)) of the solid particles (Singh et al., 2020). Slurry was also prepared for the different particle sizes ranges which lies in range <75, 75–106, 106–150 and >150 \( \mu m \). SEM images of these particle size ranges are shown in Figure 3. The present study deals with the application of mining industry where pumping sand is done to the sites at higher concentrations. So, concentration is taken more than 30 wt.%. Centrifugal pumps are operated at velocities used for experiments in present study by establishing the different rotational speeds of pot tester.

5. Results and discussion

5.1 Optimization of Mo\(_2\)C feedstock in WC-CoCr

The mean effect plot for S/N ratios of SE generated by silt slurry is represented by Figure 4(a). The S/N ratios obtained for SE by sand slurry at different input parameters are listed in Table 3. From Figure 4(a), it can be observed that the order of S/N ratio of percentage addition of Mo\(_2\)C in WC-CoCr for the SE was found as 3 wt.% > 1 wt.% > 2 wt.% > 4 wt.%.

However, the 3% addition of Mo\(_2\)C showed the minimum S/N ratio, i.e. an optimized percentage of Mo\(_2\)C in WC-CoCr.

5.2 Analysis of variance

Analysis of variance technique was used on the experimental data to statistically compare the significance of the influencing
parameters. The variance results with \( p \)- and \( F \)-values are listed in Table 4a. The higher \( F \)-values show that the process parameters have a significant impact on the response parameter. Results show that the \( p \)-value for all the four process parameters approaches to zero which indicates that the SE is a function of all of the input parameters that perform significantly. The regression value of Taguchi’s model is listed in Table 4(b). This indicates the \( R^2 \) was found as 99.96% which lies in a 95% level of confidence that delivers the precision of Taguchi’s model which can be also confirmed from the probability plot shown in Figure 4(b).

5.3 Response of different parameters
The results of various process parameters that affect the SE by solid particles are listed in Table 4(c). Figure 4(c, d) represents the 3D plots of SE with respect to influencing parameters. The order of delta was found as velocity > Mo\(_2\)C addition > particle size > solid concentration. The value of delta depicts that the velocity is the most influencing parameter amongst other parameters. However, the kinetic energy of particles increases owing to the increase in their velocity which consequently contributes to bombardment on the testing specimen with a high impact. A similar type of observation was reported by some researchers in recent studies (Desale et al., 2005; Shibe and Chawla, 2019).

5.4 Surface examination of as-sprayed coating
Figure 5(a) represents the surface microstructure of as-sprayed conventional WC-10Co4Cr coating at a magnification of 1000×. The microstructure depicts that the coating region was dense; it seems that the WC-matrix and the reinforcement Co/Cr phase were melted in spraying process. However, the unmelted particles can be seen negligible on as-sprayed surface. Figure 5(b) represents the surface microstructure of newly developed as-sprayed Mo\(_2\)C-based WC-CoCr coating at a
magnification of 1000×. The 2D/3D surface profiles represent the irregularities as well as surface waviness of as-sprayed of Mo2C-based WC-10Co4Cr coating. In Figure 5(c), it can be also observed that the irregular-splats region that indicates the presence of a lamellate microstructure of coating. By comparison, the peaks and depths in surface profile of conventional WC-10Co4Cr coating was higher as compared to Mo2C-based WC-CoCr coating. Similar type of observation

Table 4 Results from Taguchi’s model

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<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Adj MS</th>
<th>F-value</th>
<th>P-value</th>
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<td>124.981</td>
<td>41.6602</td>
<td>1309.82</td>
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<td>Concentration</td>
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<td>15.730</td>
<td>5.2433</td>
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<tr>
<td>Particle size</td>
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<td>50.179</td>
<td>16.7265</td>
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<tr>
<td>Mo2C addition</td>
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<td>76.515</td>
<td>25.5048</td>
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<tr>
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<td>0.095</td>
<td>0.0318</td>
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Summary of Taguchi’s model

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<tr>
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<td>99.82%</td>
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Response table for signal-to-noise ratios

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<td>75.60</td>
<td>78.10</td>
<td>76.43</td>
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</tr>
<tr>
<td>Delta</td>
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<td>4.60</td>
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<tr>
<td>Rank</td>
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can be made from 3D surface plots. This elaborated that the newly developed coating was denser than the conventional WC-CoCr coating.

5.5 X-ray diffraction of as-sprayed coating
Figure 5(c) represents the XRD pattern of coating as-sprayed Mo$_2$C-based WC-10CoCr coating. A broad diffraction peak appears in the XRD pattern as the 2θ approaches 37.9361° which indicates the presence of carbide, i.e. WC phase. It is also observed that the addition of Mo$_2$C caused a change in the crystalline structure of conventional WC-CoCr cermet coating. WC-CoCr coating blend with 3% Mo$_2$C powder forms the crystalline phases like γ-Mo (FCC), Co$_7$W$_6$ and W$_2$CoMo$_5$.

5.6 Cross-sectional examination of as-sprayed coating
Figure 6 represents the cross-sectional SEM image of Mo$_2$C-based WC-CoCr coating. The average coating thickness was measured as 165–200 μm. In the EDS area map, the major region covered by as-sprayed coatings was WC-phase. The Mo$_2$C addition in WC-CoCr coating increased the presence of carbon in the coated surface which gives rise to addition carbides in the coated surface, as confirmed from the XRD pattern.

5.7 Microhardness and microhardness of as-sprayed coating
The microhardness and roughness material and coatings are shown in Figure 7. The $R_a$ value (length of testing = 1.25 mm) of Mo$_2$C-based WC-CoCr coating was found lowered than conventional WC-CoCr coating. However, the Mo$_2$C-based WC-CoCr coating provides better microhardness, i.e. 0.069% as compared to conventional WC-CoCr coating.

5.8 Coating porosity
Coating porosity of WC-CoCr coating with 0, 1, 2, 3 and 4 wt. % addition of Mo$_2$C was measured as 0.26%, 0.27%, 0.29%, 0.29% and 0.31 ± 0.06%, respectively. The porosity of WC-CoCr coating drops with the addition of Mo$_2$C.

5.9 Fracture toughness
Fracture toughness of WC-CoCr coating was measured as 6.92 ± 0.5 MPa m$^{1/2}$. However, the fracture toughness improves with the addition of Mo$_2$C. Fracture toughness of WC-CoCr coating with 1, 2, 3 and 4 wt.% addition of Mo$_2$C was measured as 7.13 ± 0.4, 9.85 ± 0.4, 11.75 ± 0.3 and 12.32 ± 0.2 MPa m$^{1/2}$, respectively.

5.10 Slurry erosion performance analysis of coating
Figure 8 represents a comparison of SE performance of conventional and Mo$_2$C-based WC-CoCr coating at different impact angles. The experimentation was carried for a time period of 3 h by developing impact angle arrangements shown in Figure 8. Figure 8 shows that the 3% Mo$_2$C-based WC-CoCr coating exhibits better SE resistance than the conventional WC-CoCr coating. The pattern of change in SE
with impact angle was found increasing and the maximum value was found at an impact angle of $60^\circ$ which indicates the brittle failure of erosion. This occurs possibly because of the reason that the Mo$_2$C serves an additional intersplat adhesion thus, the formation of a denser surface can help reduce the wear damages. Also, the Mo$_2$C contributes to carburizing of the Co/Cr phase, as observed in the XRD pattern. The formation of additional carbides is helpful to avoid the deformations that contribute to erosion.

5.11 Microstructure of slurry erosion mechanisms
Numerous researchers (Desale et al., 2005) reported the major mechanics responsible for erosion are abrasion, cutting, plowing, cracking, pitting, chiseling, pullout and so on. Figure 9(a) represents the microstructure of SE mechanisms for $d = 45.6 \, \mu m$. The removal of material from the surface of the specimen took place by the action of microcutting, crater, crack, pull-out and pits mechanisms, as seen in Figure 9(a, b). The presence of the erodent particles was also seen in the SEM image which was because of the embedment of hard solid particles in Co/Cr matrix. From Figure 9(c), the EDS shows the eroded section contains C 19.39%, Cr 3.35%, Co 9.90% and W 66.36%. The Co/Cr phase seems to be deteriorated in the EDS map. It can be observed that more surface waviness was observed in the 2D surface profile augmenting in the pull-out sections, as shown in Figure 9(d). Figure 10(a) shows that
the deep craters, pitting on smooth splat-surface and cracks were appeared on the Mo$_2$C-based WC-CoCr coated surface for $d = 257.8 \, \mu m$. The cracks can be seen as depth and crater regions showed peaks in the 3D surface plot (Figure 10b). The EDS map shown in Figure 10(c) shows the eroded section contains C 29.70%, Fe 9.65%, Cr 1.04%, Co 9.74%, Mo 2.76% and W 47.10%. The EDS maps show the presence of Fe in eroded section; however, the C was found in higher proportion which reflects the embedment of erodent in the eroded region (Singh et al., 2019a).

Numerous researchers discussed that the microcutting, pull-out and crack initiation-propagation-fracture are the major mechanisms on the surface of brittle materials (Gupta et al., 1995; Thakur et al., 2011; Singh et al., 2019b). From the SE mechanism results, the craters, microcutting and cracking were the secondary mechanisms of material failure. The additional proportion of Mo$_2$C delivers a resistance against the tendency for material brake-outs (García et al., 2019). Moreover, the addition of Mo$_2$C helped in the formation of additional carbides which were helpful to avoid the plastic deformation and plowing mechanisms of SE. So, the...
SE mechanisms of the newly developed Mo$_2$C-based WC-CoCr depict the brittle mode failure.

6. Conclusions

The following conclusions can be drawn based on SE results:

- The microhardness of bare, conventional WC-CoCr and Mo$_2$C-based WC-CoCr coated impeller steel was found as 197 ± 8.17, 1,156 ± 8.13 and 1,182 ± 6.34 Hv, respectively.
- The erosion wear was increased with the increase in velocity and weighted mean size of slurry particles.
- The deposition of conventional WC-CoCr coating had improved the wear resistance of impeller steel (SS 316L) by 9.98%.
- The percentage of Mo$_2$C in WC-CoCr was optimized as 3% by weight. The SE performance of conventional WC-CoCr coating was improved as 69.6% by the addition of 3% Mo$_2$C.
- The additional proportion of Mo$_2$C delivers a resistance against the tendency for material brake-outs which helped in the formation of additional carbides that are helpful to avoid the plastic deformation and plowing mechanisms of SE.
- Microscopically, the craters, microcutting and cracking were the secondary mechanisms of material failure on Mo$_2$C-based WC-CoCr coating that refers to the brittle-mode of erosion failure.

References

Mo$_2$C reinforced WC-CoCr coating

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