EFFECT OF SLIDING VELOCITY AND PLASMA SPRAYING PARAMETERS ON WEAR RESISTANCE OF NiCrBSiCFe PLASMA SPRAYED ON AUSTENITIC STAINLESS STEEL AT HIGH TEMPERATURE

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The tribological tests were carried out on AISI 316 austenitic stainless steel (ASS) plasma coated with NiCrBSiCFe alloy powder under two set of plasma spraying parameters (PSP 1 and PSP 2) using a pin-on-disc-apparatus. EN 8 medium carbon steel was used as a counterface material. The tests were carried out at load of 20 N with sliding velocities of 1m/s and 2m/s at room temperature (35°), 150°C, 250°C and 350°C. Metallographic characterization was carried out by optical microscope (OM) and Scanning electron microscope (SEM). Between PSP 1 and PSP2, a stand-off distance of 125 mm (PSPI) was found to be more suitable for producing uniform lamellar microstructure with fewer amounts of pores with better wear resistance. The wear rate at 1m/s was comparatively more than 2m/s due to the adhesive wear and material softening. The worn debris during sliding at 350°C turn in to oxides which further behaves like a protective and lubricative film eliminating the chances of severe material loss. SEM was used to characterise the worn track and to identify the wear mechanism.

Keywords: AISI 316 ASS, NiCrBSiCFe, sliding velocity, stand-off distance, abrasive wear, plasma spraying

1. Introduction

Austenitic stainless steels are widely employed in nuclear reactors, biomedical implants, machinery for chemical and food processing industries. In nuclear industries, engineering components namely control rod actuator mechanisms and valves made of stainless steel encountered unlubricated contacts against mild steel at 200°C. The coatings without cobalt (Co60) were preferred for hard facings since it is a major contributor of radiation exposure [1]. As austenitic stainless steels exhibit poor wear resistance, surface modification techniques were used to improve its tribological properties. The interacting solid surfaces with the interfacing materials and environment result in material loss from the surface. Relative sliding between the contacting surfaces leads to the rupture of these junctions and subsequent material transfer from one surface to the other, in addition to the production of debris and material loss. The plasticity-dominated sliding wear prevails at lower sliding velocities [2].

A blasted austenitic stainless steel plate (JIS-SUS304) has been characterized and compared to the scraped and non-blasted specimens. A martensite phase is formed in the surface layer of both blasted and scraped specimens. It is concluded that the deterioration of corrosion resistance of austenitic stainless steel through blasting is caused by the roughed morphology of the surface [3]. Special attention has been paid to NiCrBSi alloys, since they provide an excellent wear and corrosion resistance at high temperatures. The influence of several factors such as load, temperature, presence of reinforcement particles and the type of thermal spray technique on the wear behaviour of NiCrBSi alloy was studied by Rodriguez et al. [4]. The effects of boronizing on plain carbon steel AISI 1018; high-strength alloy steel AISI 4340 and AISI 304 ASS was investigated. The presence of boronized coatings on ferrous alloys improved their microhardness, oxidation resistance and corrosion resistance [5]. TiCrC-FeCr composite coating was deposited on steel and titanium alloy by plasma method. The composition, structure and tribological properties of these coatings are studied in comparison with traditional materials based on the Ni-Cr alloy. Titanium-chromium carbide has greater wear resistance than that of Ni-Cr alloys with almost equal friction coefficients [6]. The sliding wear of AISI 304 and AISI 316 austenitic stainless steels in pin-on-disc equipment was studied as a function of applied load (6-20N) and tangential velocity (0.07–0.81 m/s). Worn surfaces and wear debris were analysed through SEM, XRD, Mossbauer spectroscopy, surface temperature and instrumented indentation.

Results indicated that plasticity-dominated wear (metallic particle oxidation, adhesive and mixed wear) as the sliding wear mechanisms [7]. The influence of a post spray heat treatment on the microstructure,
microhardness and abrasive wear behaviour of the flame sprayed Ni-WC coating deposited on the mild steel was studied. As the normal load was increased, the wear rate was also increased. The SEM study indicated that the wear largely takes place by groove formation and scoring of eutectic matrix and the fragmentation of the carbide particles [8].

The influence of the addition of chromium carbide (CrC) particles on the microstructure, microhardness and abrasive wear behaviour of flame sprayed NiCrSiB coatings deposited on low carbon steel substrate was studied. The addition of CrC reduces the wear rate from three to eightfold. Wear resistance was greater against coarse abrasives at high loads than against fine abrasives. Heat treatment of both unmodified and CrC modified powder coatings deteriorated the abrasive wear resistance [9]. Ni-Al-SiC feed stock powder containing 12.5% SiC was plasma sprayed on CK 45 steel substrates. The coatings were composed of different intermetallics including Ni-Al and Ni3Al. The mean hardness of the coating was 567 HV.

It was reported that by increasing current density of atmospheric plasma spraying (APS), the coating/substrate adhesive strength was increased [10]. Plasma-sprayed Ni-50% Cr, plasma-sprayed Al2O3-13%TiO2 and high-velocity oxygen-fuel sprayed (HVOF) WC-17%Co coatings for enhancing the wear resistance and the corrosion protective nature of a diamond-like carbon (DLC)-based thin film were deposited onto a carbon steel substrate. At 300°C, the DLC-based film on the Al2O3-13%TiO2 interlayer offers the best tribological performance due to the increased toughness of the ceramic interlayer at this temperature [11]. Glow discharge (GD) nitrocarburizing, at low carbon content and different working temperatures, was performed on AISI 316L and AISI 304 stainless steels. At working temperatures higher than 400°C, roughness increased and wear was limited to asperity compaction. Wear was reduced by up to a factor of 5 in treated steels [12]. Industrial alternative application to hard chromium plating was proposed as NiCrBSi coating. Tribological characterization was carried out in order to determine the alternative potential of NiCrBSi coatings compared to electrolytic hard chromium plating, in applications to resist wear [13]. NiCrBSi was deposited on 0Cr13Ni5Mo stainless steel using the activated combustion high velocity air fuel (AC-HVAF) technique. The structure and morphologies of the Ni-based coatings were investigated by XRD, SEM and EDS [14].

The present study aims to analyse the influence of sliding velocity and plasma spraying parameters on the high temperature wear properties of NiCrBSiCFe plasma sprayed on AISI 316 ASS. The microstructure of the coating was studied and the microhardness was measured with respect to the plasma spraying parameters. The worn surface morphology were examined by SEM and correlated with the experimental results.

2. Experimental Procedure

2.1. Materials

AISI 316 ASS in as-received condition was used as a substrate by machining to a dimension of 100 mm diameter with 4 mm thickness. Degreasing of surfaces was performed using acetone. The substrate was then grit blasted by Al2O3 in order to improve the roughness in the order of 10–12 µm. EN8 medium carbon steel was used as a counterface material. NiCrBSiCFe self fluxing alloy was used as the feedstock powder. The average size of the powder was 63.72 µm. The chemical compositions of the materials used are shown in Table 1.

<table>
<thead>
<tr>
<th>Elements</th>
<th>Ni</th>
<th>Cr</th>
<th>B</th>
<th>Si</th>
<th>C</th>
<th>Fe</th>
<th>S</th>
<th>Mn</th>
<th>Mo</th>
<th>P</th>
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<tr>
<td>AISI 316</td>
<td>14</td>
<td>18</td>
<td>--</td>
<td>1.0</td>
<td>0.08</td>
<td>Bal.</td>
<td>0.03</td>
<td>2.00</td>
<td>3.00</td>
<td>0.045</td>
</tr>
<tr>
<td>Substrate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NiCrBSiCFe Powder</td>
<td>Bal.</td>
<td>13.3</td>
<td>3.1</td>
<td>3.9</td>
<td>0.5</td>
<td>3.7</td>
<td>--</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EN-8 counterbody</td>
<td>--</td>
<td>--</td>
<td>--</td>
<td>0.15</td>
<td>0.35</td>
<td>Bal.</td>
<td>--</td>
<td>0.6</td>
<td>--</td>
<td>0.04</td>
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</table>

2.2. Plasma Spraying

Plasma spraying is a high-energy process in which a high current arc is generated within the torch and a gas is injected into the arc chamber, where it is heated and converted into high temperature plasma. The plasma spraying parameters (PSP-1 and PSP-2) used for coating on AISI 316 ASS are tabulated (Table 2). The stand-off distance, current and voltage parameters are varied to study the influence on coating
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characteristics. The NiCrBSiCFe alloy powder was fed on the 4 MP dual powder feed unit (SST-25). The Metco spray gun (SST-24) was stationary and the AISI 316 ASS specimen was mounted on a rotating table. The powder was introduced in the plasma jet generated from the plasma torch. The coating feedstock material was injected vertically into the plasma jet by argon (Ar) carrier gas for primary flow and hydrogen gas (H2) for secondary flow. In the plasma jet, the temperature is around 6,600°C to 16,600°C which is responsible for melting. The particle flight in velocity up to 600 m/s is responsible for propelling towards the AISI 316 substrate [15]. The plasma coating was performed ~ 500 µm thickness.

Table 2. Plasma spraying parameters

<table>
<thead>
<tr>
<th>Plasma spray parameter</th>
<th>PSP 1</th>
<th>PSP 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td>AISI 316 ASS</td>
<td>AISI 316 ASS</td>
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<tr>
<td>D.C. Current (A)</td>
<td>480</td>
<td>500</td>
</tr>
<tr>
<td>D.C. Volts (v)</td>
<td>70</td>
<td>60</td>
</tr>
<tr>
<td>Primary gas flow rate (slpm)</td>
<td>Argon 150</td>
<td>150</td>
</tr>
<tr>
<td>Primary gas flow rate (slpm)</td>
<td>Hydrogen 15</td>
<td>18</td>
</tr>
<tr>
<td>Feedstock carrier gas flow rate (slpm)</td>
<td>Argon 37</td>
<td>37</td>
</tr>
<tr>
<td>Feedstock carrier gas flow rate (slpm)</td>
<td>Argon 120</td>
<td>120</td>
</tr>
<tr>
<td>Stand-off spray distance (mm)</td>
<td>125</td>
<td>100</td>
</tr>
<tr>
<td>Scanning velocity (mm/sec)</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>Coating thickness (µm)</td>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

2.3. Wear Tests

Dry sliding tests were carried out using a DUCOM TR-20-M-106 pin-on-disc test rig. The test was performed as per ASTM standard G99-05 [16] with coating on the disc rather than on the pin material to simulate wear behaviour in specific application listed elsewhere [1]. The pins, with a diameter of 6 mm and a height of 31 mm, were machined from EN8 medium carbon steel as a counterface material. The NiCrBSiCFe coated AISI 316 ASS discs with two parameters were used as samples. The experiments were carried at loads of 20N and 40 N at different temperatures such as room temperature, 150°C, 250°C and 350°C. The sliding velocity was 1m/s and the sliding distance was 2000 m. The LVDT (linear variable differential transducer) was positioned on the weights to measure displacement and the load cell to sense the tangential force. An induction coil was inbuilt in the system to raise the temperature to the desired levels to carry out the experiment.

The wear and frictional force were simultaneously recorded by data acquisition system. The wear resistance was calculated by cumulative weight residual method. The mass loss of the uncoated and NiCrBSiCFe coated discs were measured after the completion of every cycle of experiment with an electronic weighing balance of 0.1 mg accuracy. The volume loss was calculated by the equation (1). The wear rate and wear resistance were calculated by equations 3 and 4, respectively. Coefficient of Friction (CoF) was calculated by the equation (5). The set of calculation is:

\[
Volume\; loss\; (mm^3) = \left(\frac{Mass\; loss}{\rho_1}\right) \times 1000 ,\tag{1}
\]

\[
Coating\; density\; (\rho) = \rho_1 \times \left(\frac{m_a}{m_a - m_j}\right) ,\tag{2}
\]

where \(\rho_1\) is the density of water 1 g/cm³ at room temperature, \(m_a\) the weight of the plasma coating in air (g) and \(m_j\) is the weight of plasma coating in water (g).

\[
Wear\; rate\; (mm^3/m) = \left(\frac{Volume\; loss}{Sliding\; distance}\right) ,\tag{3}
\]

\[
Wear\; resistance\; (m/mm^3) = \left(\frac{Sliding\; distance}{Volume\; loss}\right) ,\tag{4}
\]

\[
Coefficient\; of\; Friction, \mu = \left(\frac{F}{N}\right),\tag{5}
\]

where \(F\) is the Frictional force and \(N\) is normal applied load in Newtons.
2.4. Coating Characterisation: Microstructural and Microhardness Characterisation

The plasma sprayed AISI 316 ASS samples were sectioned, polished and etched with Nital. The etched specimens were studied by optical microscopy (OM). The micrograph of EN-8 medium carbon steel was also analysed. The as-sprayed specimens of PSP-1 and PSP-2 were first cut suitably and analysed by SEM (HITACHI S 3000H). The worn tracks of the plasma sprayed specimens were also analysed using SEM to identify the mode of material loss during sliding at different temperatures. The worn debris of the NiCrBSiCFe coated discs at 350° were collected after the completion of the experiments. The morphology of the wear asperities collected were characterised by SEM. The microhardness of the plasma sprayed specimens was measured using Zwick MHT Vickers hardness tester at a load of 300 g for 20 seconds.

3. Results and Discussions

3.1. Microstructural Characterisation of the Coating

The largely employed Ni-based powder belongs to the NiBSi system with the addition of other alloying elements like C, Fe and Cr. The addition of chromium enhances the corrosion resistance at elevated temperatures and increases the hardness of the coating by the formation of hard phases. Boron decreases the melting temperature and contributes to the formation of hard phases. Silicon is added to increase the self-fluxing properties. Carbon produces hard carbides with elevated hardness, thus improving the wear resistance of the coatings. Solid solution of chrome in nickel with dispersed phases of borides, silicides and carbon borides forms a base of the NiCrBSiCFe layers.

The cross-sectional microstructures of PSP-1 and PSP-2 are shown on Figure 1(a) and (b). PSP-1 with a stand-off distance of 125 mm resulted in relatively fine lamellar microstructure with uniform molten splat formations and the even distribution of NiCrBSiCFe layers (Figure 1(a)). This microstructure resists loss of material in a better manner than PSP-2.

The unmelted spherical powder particles and pores were visible in PSP-2 sprayed relatively with a shorter stand-off distance of 100mm. This shorter stand-off distance prevents the powder from complete melting and the flight in velocity was relatively reduced. Formation of splats by the impact of spherical particles is visible in PSP-1 (Figure 1(b)). In PSP-2, small voids and unmelted particles are present which is unfavourable to the coating performance.

3.2. Micro Hardness Characterisation

The initial hardness of the AISI 316 and EN 8 medium carbon steel pins was 223 HV0.3 and 302HV0.3, respectively. The obtained microhardness of the PSP-1 and PSP-2 are shown on Figure 2. With the increase in the stand-off distance, the microhardness also increases. The microhardness of PSP-2 with a shorter stand-off distance of 100mm was relatively lower at 780 HV0.3 whereas the microhardness of PSP-1 with 25 mm more stand-off distance than PSP-2 was relatively higher at 823 HV0.3. The microhardness values are also in direct correlation with the coating microstructure. A relatively higher value
of the microhardness is a representative phenomenon of presence of adequate lamellar structure with high cohesion strength between the layers and high adhesion strength on the coating/substrate interface. The spray distance of 125 mm was sufficient enough to enable adequate melting and flow of the powder and higher microhardness [17].

![Microhardness variation of PSP-1 and PSP-2 as a function of the distance from the surface](image)

**Figure 2.** Microhardness variation of PSP-1 and PSP-2 as a function of the distance from the surface

### 3.3. Characterisation of Wear at Different Temperatures

The wear of the uncoated, PSP-1 and PSP-2 samples at room temperature with 20 N load at sliding velocity 1m/s is shown on Figure 3(a). It is observed that the plasma sprayed samples possess good wear resistance when compared with the uncoated samples. The uncoated samples worn at sliding velocity of 1m/s showed greater wear of 1000 µm. The superior wear resistance of NiCrBSiCFe coated samples was due to the presence of hard intermetallics like Ni₃B and Fe₃B formed during spraying. Compared to PSP-2, PSP-1 exhibits higher wear resistance. This may be attributed to the higher hardness of PSP-1 samples. The wear rate of the uncoated, PSP-1 and PSP-2 samples was slightly higher at 150°C than at room temperature for all tested samples which is shown on Figure 3 (b). At 250°C, the wear rate observed to be higher compared to the other test conditions (Figure 4 (a)). At 1 m/s sliding velocity, material softening might have taken place which promotes three body abrasive wear with seizure. Sliding at this temperature might have led to high local pressure between contacting asperities resulting in plastic deformation, adhesion and the consequent formation of local junctions.

The more plastic deformation associated with the wear is responsible for the higher wear rate in this temperature. The worn debris during sliding at 350°C turn in to oxides which further behaves like a protective and lubricative film eliminating the chances of severe material loss. The improved wear resistance of both PSP-1 and PSP-2 samples are justified by the oxide formations and is shown on Figure 4(b). The samples worn at sliding velocity 2m/s at room temperature, 150°C, 250°C and 350°C showed relatively lesser wear with respect to time (Figure 5(a) and (b)) and (Figure 6(a) and (b)). The reason for the comparatively lesser wear is due to the slipping that occurs at higher velocity (2m/s). Slipping excludes the chances of severe wear and improves the wear resistance.
Figure 3. Variation of wear with respect to time at sliding velocity 1m/s: (a) room temperature; (b) 150°C
Figure 4. Variation of wear with respect to time at sliding velocity 1m/s: (a) 250°C; (b) 350°C
Figure 5. Variation of wear with respect to time at sliding velocity 2m/s: (a) room temperature; (b) 150°C
Figure 6. Variation of wear with respect to time at sliding velocity 2m/s: (a) 250°C; (b) 350°C.
The wear resistances were calculated at sliding velocities at 1 m/s and 2 m/s for different temperatures with an applied load of 20 N are shown on Figure 7 (a) and (b). The higher wear resistance values were obtained for samples worn at 350°C in both the spraying parameters. When the plasma sprayed parameters are compared, the average wear resistance of PSP-1 samples are marginally higher (501 m/mm³) than PSP-2 (456 m/mm³) at 1 m/s sliding velocity. Similarly, the average wear resistance of PSP-1 samples are marginally higher (575 m/mm³) than PSP-2 (481 m/mm³) at 2 m/s sliding velocity. At sliding velocity 2 m/s the wear resistances of samples were found to be greater than the samples worn at 1 m/s sliding velocity.

![Figure 7. Wear resistance of uncoated, PSP-1 and PSP-2 samples: (a) sliding velocity 1m/s; (b) sliding velocity 2m/s](image)

3.4. Worn Surface Characterisation by SEM

Figure 8(a)-(b) shows the wear tracks of sample worn with 20 N load and at different temperatures at sliding velocity 1 m/s and 2 m/s of PSP-1 samples. Coated samples sled with 1 m/s velocity in room temperature, the worn surface of the sample is characterised by delamination of layers. Debris is sparsely seen on Figure 8(a). In contrast samples worn at 2 m/s sliding velocity show shallow grooves parallel to the sliding direction. The sliding resulted with minimal amount of plastic deformation due to slipping (Figure 8(b)). At 150°C, samples worn at sliding velocity of 1 m/s the surface is characterised by flaking and exfoliation.

![Figure 8. Worn surface of sample at room temperature: (a) sliding velocity 1m/s; (b) sliding velocity 2m/s](image)

Further subsurface cracking is visible due to the adhesive wear at lower sliding velocity and is shown on Figure 9(a). The samples worn at sliding velocity 2 m/s showed shallow prow formation, which run parallel to the sliding direction (Figure 9(b)).
This mode of wear promotes minimal material loss. At 250°C, samples worn at 1 m/s sliding velocity, the surface is characterised by ploughing and prow formations. Both these modes promote more material loss which is shown on Figure 10(a). The samples worn at sliding velocity of 2 m/s shows ploughings with lesser depth and featureless plateaus conclude that lesser wear has taken place (Figure 10(b)).

The worn surface of the samples sled with 1 m/s at 350°C shows oxide layer formation with microcracks as it is shown on Figure 11(a). The oxides formed were peeled off from the surface and promotes further wear. These oxides promote cracking. The cracks encourage more material loss at lower velocity. The samples worn at 2 m/s sliding velocity showed the presence of oxide layer formation. The oxide layers are stable with no visible microcracks (Figure 11(b)).
Lateral spreading of the material on consecutive runs turn in to oxide layers which act as a protective and lubricative layer thereby preventing more material loss.

Conclusions

From the high temperature dry sliding wear experiments conducted on uncoated and AISI 316 ASS substrates plasma sprayed under PSP-1 and PSP-2 parameters at various operating temperatures, the following conclusions can be drawn.

- The NiCrBSiCFe was plasma sprayed in two parameters (PSP-1 and PSP-2) on AISI 316 ASS to a thickness of up to 500 µm. The coatings exhibited metallurgically good bond strength to the substrate and free from any defects.
- PSP-1 with a stand-off distance of 125 mm showed fine lamellar microstructure with evenly dispersed phases of NiCrBSiCFe on the coating and PSP-2 shows sparse presence of unmelted powders included with pores at the interface.
- The microhardness of PSP-1 and PSP-2 was improved to 823 HV0.3 and 780 HV0.3, respectively. This improvement in hardness primarily responsible for higher wear resistance of the coated samples.
- The average wear resistance value of PSP-1 at sliding velocity 1 and 2 m/s are 501 and 575 m/mm³, respectively. The average wear resistance value of PSP-2 at sliding velocity 1 and 2 m/s are 456 and 481 m/mm³, respectively.
- The effect of sliding velocity is very significant at different operating temperatures. Wear rate was found to be inversely proportional with the sliding velocity as it shows increased wear resistance at 2m/s when compared to 1m/s, irrespective of the spraying parameters.
- At 250°C, material softening might promote three body abrasive wear and subsequently lead to severe adhesive wear upon further sliding with no visible oxide layers in 1m/s sliding velocity.
- The samples worn at 2m/s sliding velocity showed shallow grooves, ploughing and prow formations due to the sliding. This may be attributed to the reason for superior wear resistance when compared with lower sliding velocity (1m/s).
- The samples worn at 1m/s sliding velocity showed exfoliation mode of wear mechanism with deeper prow formation as a result of abrasive wear is responsible for the higher wear rate and poor wear resistance.
- The oxide layers formed at 350°C on consecutive sliding, acted as a protective and lubricative layer more prominently at 2m/s sliding velocity rather than at 1m/s sliding velocity.

References


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