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Studies on the Sliding Wear Performance of Plasma Spray Ni-20Cr and Ni_3Al Coatings

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Two metallic powders namely Ni-20Cr and Ni_3Al were coated on AISI 309 SS steel by shrouded plasma spray process. The wear behavior of the bare, Ni-20Cr and Ni_3Al-coated AISI 309 SS steel was investigated according to ASTM Standard G99-03 on a Pin-on-Disc Wear Test Rig. The wear tests were carried out at normal loads of 30 and 50 N with a sliding velocity of 1 m/s. Cumulative wear rate and coefficient of friction (μ) were calculated for all the cases. The worn-out surfaces were then examined by scanning electron microscopy analysis. Both the as-sprayed coatings exhibited typical splat morphology. The XRD analysis indicated the formation of Ni phase for the Ni-20Cr coating and Ni_3Al phase for the Ni_3Al coating. It has been concluded that the plasma-sprayed Ni-20Cr and Ni_3Al coatings can be useful to reduce the wear rate of AISI 309 SS steel. The coatings were found to be adherent to the substrate steel during the wear tests. The plasma-sprayed Ni_3Al coating has been recommended as a better choice to reduce the wear of AISI 309 SS steel, in comparison with the Ni-20Cr coating.

Keywords APS coatings, APS of sour environments, boiler plants, coating-substrate interaction, corrosion, properties of coatings

1. Introduction

Wear is a process of removal of material from one or both of two solid surfaces in solid state contact (Ref 1). These wear related problems can be minimized mostly by using high-cost wear-resistant alloys/metals better than the existing low-cost alloys or by improving the wear and corrosion resistance of the existing metals and alloys by surface modifications. As the wear is a surface phenomenon and occurs mostly at outer surfaces, it is more appropriate and economical to use latter method of making surface modification than using the former one.

Among the various commercially viable surface coating techniques, plasma spraying fosters progress in both development of materials and modern coating technology because of advances in powder and wire productions. The advanced plasma technique has many advantages such as high productivity for thick-coating films of more than 100 μm and good applicability for a wide range of coating materials including ceramic powder, further the process does not cause degradation of the mechanical properties of the alloy substrate (Ref 2). Plasma spraying is a well-established means of forming thick coatings used, for instance, for their resistance to wear, corrosion friction, and ionic conduction properties. They are used in many industrial applications; to improve the abrasive, erosive, and sliding wear of machine components. Developments in plasma spraying techniques as well as advances in powder and wire production have resulted in surface coatings with excellent properties under service conditions, thus enlarging the field of its application (Ref 3). In this presented work on wear, the plasma spraying was implemented to improve the wear properties of AISI 309 SS steel material.

In this study, AISI 309 SS steel has been studied with reference to its wear behavior. AISI 309 SS steel is extensively used in Thermal Power Plant Components, especially in the boiler parts and the hoppers for handling pulverized coal from the coal crushers. AISI 309 SS steel plates are fixed on the inner sides of the hoppers, where they come in contact with bulk of free flowing pulverized coal mass. Therefore, they suffer heavy erosive-wear and need replacement at regular intervals. This eventually causes economic loss and downtime also. To reduce this wear problem, the plasma spray coatings have been deposited on AISI 309 SS steel and they were investigated with regard to their wear characteristics. Ni-20Cr and Ni_3Al coatings were selected to be deposited on AISI 309 SS steel substrate after a comprehensive literature survey (Ref 4-14).

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Table 1 Nominal chemical composition of AISI 309 SS

Element	Wt.%
C	0.20
Mn	2.00
P	.045
S	0.03
Si	0.75
Cr	22(min) and 24(max)
Ni	12(min) and 15(max)
Fe	Balance

Table 2 Mechanical properties of AISI 309 SS

Density ($\times$1000 kg/m^3)	8
Poisson's ratio	0.27-0.30
Elastic modulus, GPa	200
Tensile strength, MPa	515
Yield strength, MPa	205
Elongation, %	40
Reduction in area, %	50
Hardness (HRB)	95 HRB

2. Experimental Procedure

The substrate material for this study has been selected after discussion with Guru Gobind Singh Super Thermal Plant, Ropar (Punjab), India. The chosen steel material is designated as AISI 309 SS. Table 1 shows nominal chemical composition of AISI 309 SS, whereas Table 2 reports some important mechanical properties of AISI 309 SS. These data were provided by the supplier of the steel. Small pins having circular cross section of diameter 8 mm and length 50 mm were prepared from AISI 309 SS. These pins were required to perform pin-on-disk experiment at room temperature. The faces of the pins were grinded, followed by polishing with emery papers down to 1000 grit. Two types of coating powders: (1) nickel-20% chromium (Ni-20Cr) and (2) nickel and aluminum (Ni_3Al) were deposited by plasma spray process on the substrate specimens. The particle size for Ni-20Cr powder was $-45+5$ µm, whereas the Ni_3Al was prepared by mixing Ni (particle size 74 µm) and Al (fine powder) powder in stoichiometric ratio of 3:1 in a ball mill for 8 h.

The coating work was carried out by a commercial company Anod Plasma Ltd., Kanpur (India). The specimens were grit blasted with Al_2O_3 powder before being plasma sprayed. The 40 kW Miller Thermal (USA) plasma spray apparatus was used to apply the coatings. Argon was used as powder carrying as well as shielding gas. The process parameters for the shrouded plasma spray process employed for applying the coatings are summarized in Table 3. The thickness of coatings was monitored during the process of plasma spraying with a thickness gauge; Minitest-2000 made in Germany. Efforts were made to obtain coatings of uniform thickness of 100 µm.

Scanning electron microscopy (SEM) surface morphology and XRD analysis of the similar type of as-sprayed coatings have been studied earlier by the authors with a

Table 3 Parameters of the argon shrouded plasma spray process

Arc current, A	700
Arc voltage, V	35
Powder flow rate, rev./min	3.2
Spraying distance, mm	90-110
Plasma arc gas (argon), MPa	0.407
Carrier gas, MPa	0.276
Spray gun nozzle diameter, mm	6

Ni-base superalloy Superni 75 as the substrate material (Ref 15-17). Dry sliding wear tests for the uncoated and plasma-sprayed AISI 309 SS were conducted using a pin-on-disc machine (Model: Wear and Friction Monitor Tester TR-20), supplied by M/S DUCOM, Bangalore (India) according to ASTM standard G99-03. A complete description of the wear testing has been reported elsewhere (Ref 18). The wear tests were carried out for a total sliding distance of 2400 m (10 cycles of 4 min duration each), so that only the coated surface was exposed for each plasma-sprayed sample.

Tangential force was monitored continuously during the wear tests. Weight losses for the pins were measured at the end of each cycle to determine the wear loss. The wear rate data for the coated as well as uncoated specimens were plotted with respect to sliding distance to establish the wear kinetics. The specific wear rates for the materials were obtained by

$$W = \Delta w / L \rho F, \qquad \text{(Eq 1)}$$

where W denotes specific wear rates in mm^3/N m, Δw is the weight loss measured in grams, L is the sliding distance in meters, ρ the density of the worn material in g/mm^3, and F is the applied load in N. The coefficient of friction (μ) has been plotted against the sliding time to give the friction behavior of the materials, which was calculated as below:

$$\mu = \text{Frictional Force (N)/Applied Normal Load (N)}. \qquad \text{(Eq 2)}$$

Some of the worn-out surfaces were analysed by SEM analysis using a JSM scanning electron microscope (Model: JSM 6100).

3. Experimental Results

3.1 Characteristics of As-Sprayed Ni-20Cr and Ni_3Al Coatings

3.1.1 SEM Analysis. SEM morphologies for the plasma-sprayed Ni-20Cr (Ref 15, 16) and Ni_3Al (Ref 16, 17) coatings on Superni 75 substrate have been reproduced in Fig. 1(a) and (b), respectively. Since similar coatings have been deposited on AISI 309 SS substrate, it is assumed that the morphologies observed for Superni 75 would be similar to those for AISI 309 SS substrate. Microstructures revealed are typical for a plasma spray

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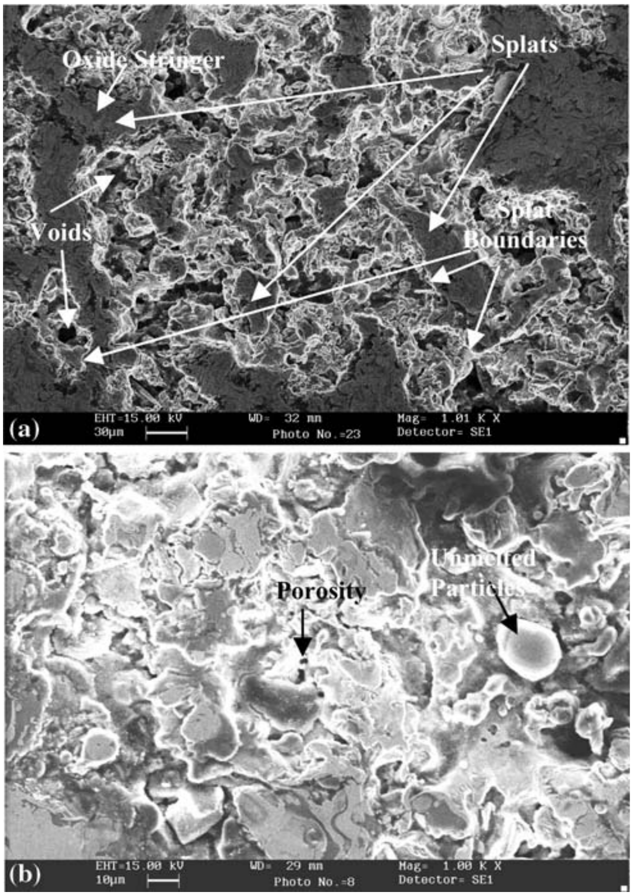

Fig. 1 SEM micrographs showing typical surface morphology of plasma-sprayed (a) Ni-20Cr coating (Ref 15, 16) and (b) Ni_3Al coating (Ref 16, 17) on Superni 75 substrate

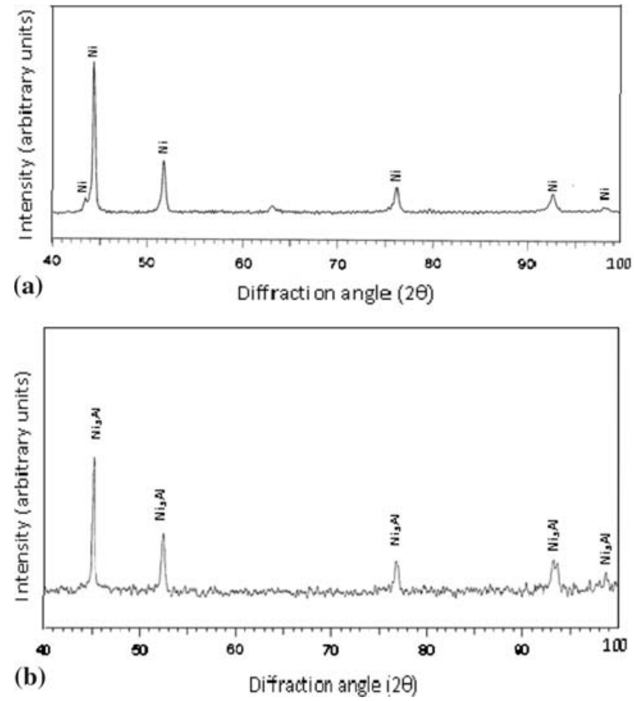

Fig. 2 X-ray diffraction patterns for the plasma-sprayed (a) Ni-20Cr coating (Ref 16) and (b) Ni_3Al coating (Ref 16, 17) on Superni 75 substrate

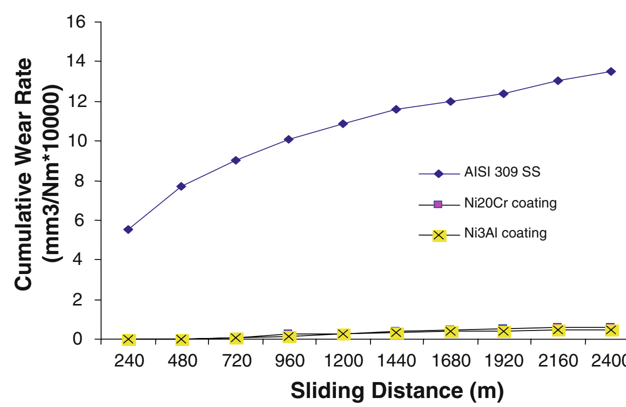

Fig. 3 Variation of CWR with sliding distance for the uncoated, the plasma-sprayed Ni-20Cr and Ni_3Al coated AISI 309 SS steel subjected to wear at normal load of 30 N and sliding velocity of 1 m/s

process consisting of splats which are irregular shaped with distinct boundaries. Most of the splats are well formed without any sign of disintegration. Presence of some oxide stringers as well as open pores has also been noticed in general in both the coatings.

3.1.2 XRD Analysis. As reported in Fig. 2(a) (Ref 16), the XRD analysis of the Ni-20Cr coating on Superni 75 revealed γ-Ni as the main phase without formation of any intermetallic phase. In the case of Ni_3Al coating on Superni 75 (Ref 16, 17), the formation of the Ni_3Al as a main phase was confirmed by the analysis as has been reproduced in Fig. 2(b).

3.2 Wear Behavior

3.2.1 Wear Behavior at a Normal Load of 30 N. The variation of the cumulative wear rate (CWR) with the sliding distance for plasma spray Ni-20Cr and Ni_3Al coated and uncoated AISI 309 SS steel has been plotted in Fig. 3. It is evident from the plots that the uncoated steel shows much higher wear rate as compared to its coated counterparts. Further, the CWR for the former case shows an approximately linearly increasing trend with increase in sliding distance, whereas in the latter cases the same has shown the tendency to become uniform. A uniform wear rate is a favorable trend from the point of view of wear resistance. Therefore, it can be concluded that the coatings are useful to enhance the wear resistance of the base steel. Furthermore, the plasma-sprayed Ni_3Al coating showed lowest CWR among these three cases. In other words, the plasma-sprayed Ni_3Al coating is better than plasma-sprayed Ni-20Cr coating under the stated conditions. The coefficient of friction (μ) determined from the frictional force, and the normal load has been plotted against the

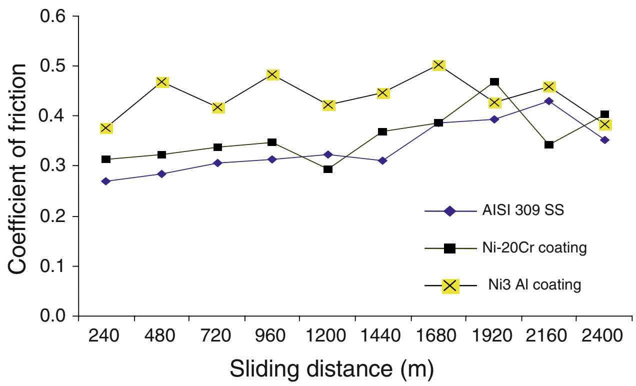

Fig. 4 Variation of coefficient of friction with sliding distance for the uncoated, the plasma-sprayed Ni-20Cr and Ni_3Al-coated AISI 309 SS steel subjected to wear at normal load of 30 N and sliding velocity of 1 m/s

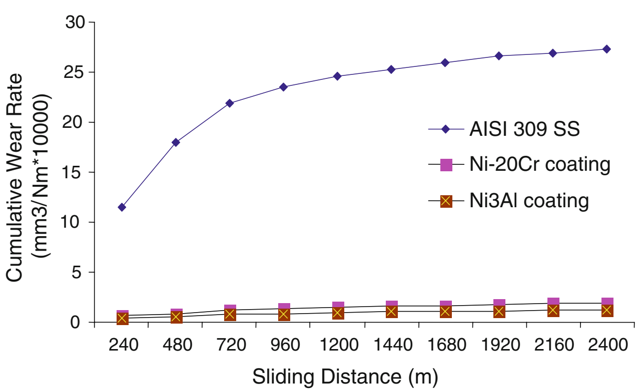

Fig. 5 Variation of CWR with sliding distance for the uncoated, the plasma-sprayed Ni-20Cr and Ni_3Al coated AISI 309 SS steel subjected to wear at normal load of 50 N and sliding velocity of 1 m/s

sliding distance for the uncoated as well as plasma-sprayed Ni-20Cr and Ni_3Al-coated AISI 309 SS steel subjected to wear testing at a normal load of 30 N and sliding velocity of 1 m/s in Fig. 4. It can be observed that the μ for the uncoated AISI 309 SS steel, as well as plasma-sprayed Ni-20Cr AISI 309 SS steel shows more abrupt changes in their values, whereas Ni_3Al-coated AISI 309 SS steel shows minor variations in its μ values. Furthermore, the Ni_3Al-coated AISI 309 SS steel has shown (Fig. 4) somewhat relatively higher values of coefficient of friction. The mean value of μ are calculated as 0.34 (SD −0.04) for the AISI 309 SS steel, 0.36 (SD −0.05) for the Ni_3Al-coated AISI 309 SS steel and, 0.44 (SD −0.04) for the Ni-20Cr-coated AISI 309 SS steel.

3.2.2 Wear Behavior at a Normal Load of 50 N. The variation of CWR with sliding distance for the plasma-sprayed Ni-20Cr and Ni_3Al coated, as well as uncoated AISI 309 SS steel has been shown in Fig. 5. It is evident from the graph that the CWR for the Ni-20Cr and Ni_3Al plasma spray-coated samples do not show significant change with wear distance, while that for the uncoated

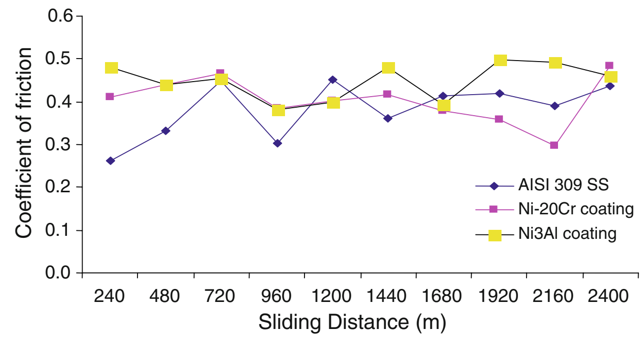

Fig. 6 Variation of coefficient of friction with sliding time of uncoated, the plasma-sprayed Ni-20Cr and Ni_3Al coated AISI 309 SS steel subjected to wear at normal load of 50 N and sliding velocity of 1 m/s

AISI 309 SS steel does, for the latter case, the CWR increases with the sliding distance. This shows that coatings are successful in enhancing the wear resistance of the base steel. It is clear that CWR for the plasma-sprayed Ni-20Cr and Ni_3Al coating do not differ significantly, however as compared to that for the AISI 309 SS steel case, the values are insignificant for both the coated samples. Moreover, the Ni_3Al coating shows slightly better wear resistance in comparison with the Ni-20Cr coating. The plots between the coefficient of friction (μ) and the sliding distance for the uncoated, as well as plasma spray Ni-20Cr and Ni_3Al-coated AISI 309 SS steel have been shown in Fig. 6. The mean value of μ for the uncoated, Ni-20Cr, and Ni_3Al-coated cases is found to be 0.38 (SD −0.06), 0.40 (SD −0.05), and 0.45 (SD −0.04), respectively.

3.3 SEM Analysis

The SEM micrographs for the worn-out surface for the uncoated AISI 309 SS steel subjected to wear at normal load of 50 N with a sliding velocity of 1 m/s after a sliding distance of 2400 m have been reported in Fig. 7(a). The SEM micrograph clearly shows the presence of wear tracks on the surfaces. The surface has become rough with unidirectional growth of the structure, probably along the direction of rotation. Moreover, it looks as a surface has lost the material in the form of microchips, probably due to ploughing of the surface by the wear debris between the contact surface of the pin and the disc. Figure 7(b) and (c) shows the surface morphology for the plasma-sprayed Ni-20Cr and Ni_3Al-coated steel samples subjected to wear at a normal load of 50 N with a sliding velocity of 1 m/s, respectively, after a total sliding distance of 2400 m. It can be perceived from comparison of these micrographs with those of similar type of as-sprayed specimens (Fig. 1) that the coatings have retained their original microstructure, by and large, even after testing. There are no signs of deformation of splats for the Ni_3Al-coated case whereas very marginal deformation is indicated in the case of the plasma-coated Ni-20Cr-coated case. This shows that the coated samples have shown significantly higher wear resistance in comparison with their uncoated counterparts.

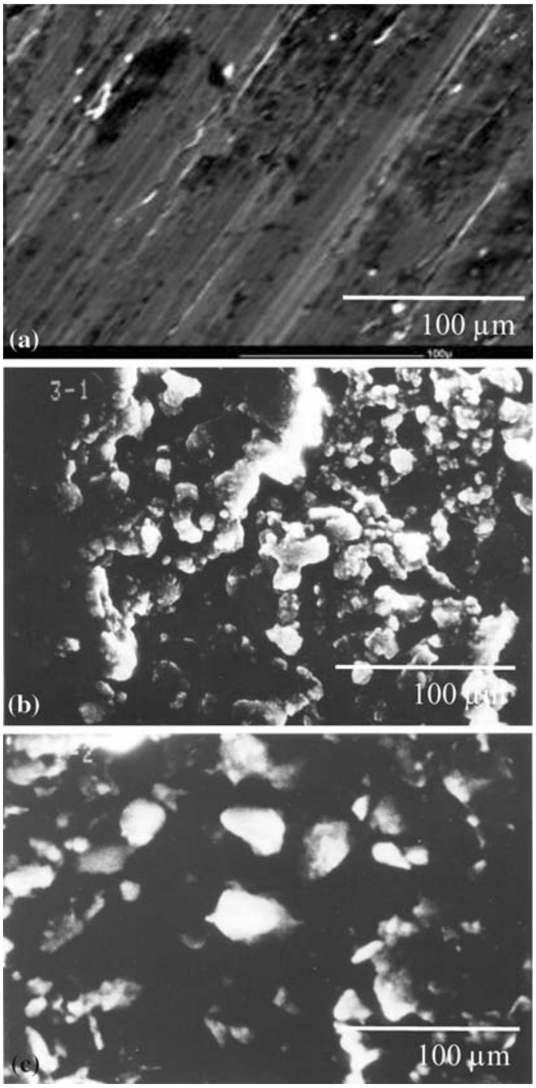

Fig. 7 SEM micrograph of the uncoated and plasma spray-coated AISI 309 SS steel subjected to wear at a normal load and sliding velocity of 1 m/s for a total sliding distance of 2400 m at normal load of 50 N. (a) Uncoated AISI 309 SS, (b) Ni-20Cr coated, and (c) Ni_3Al coated

4. Discussion

The Ni-20Cr and Ni_3Al powders were successfully deposited on AISI 309 SS substrate steel by the plasma spray process. The thickness of the coating was 100 µm in both the cases. A comprehensive discussion on phase formation and microstructure of similar coatings can be found elsewhere (Ref 15-17). The uncoated AISI 309 SS steel showed higher CWR in comparison to the plasma-sprayed Ni-20Cr and Ni_3Al-coated AISI 309 SS steel under all the investigated load variants of 30 and 50 N. Moreover, this CWR increased with increase in sliding distance for the uncoated steel, whereas the same become nearly uniform in the plasma-sprayed coated cases. This indicates that the wear resistance of the AISI 309 SS steel got increased significantly after the application of the coatings. Although the coefficient of friction has increased for the coated cases yet this increase is marginal. It has been observed from the overall results of investigation (Fig 8) that the Ni_3Al coating has shown comparatively lower CWR among the investigated case in general, under the normal load testing of magnitudes of 30 N and 50 N. Therefore, it may be concluded that the Ni_3Al coating is more wear resistant than the Ni-20Cr coating. The surface of the uncoated steel suffered damage of its contact surface in the form of micropits, which most likely may have occurred due to microploughing effect of the wear debris between the contact surface of steel and rotating disc. Similar observation has also been reported by Singh et al. (Ref 18) and Mishra (Ref 19). Whereas no such damage of the contact surfaces of the coatings has been observed. Moreover, the coatings were found to be successful in keeping their surface contact with the substrate steel when subjected to wear tests.

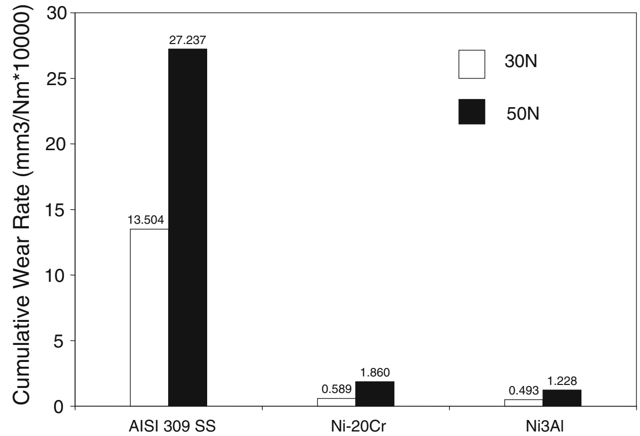

Fig. 8 Bar chart showing variation of CWR, for the uncoated, the Ni-20Cr and Ni_3Al coated steel under normal load conditions of 30 and 50 N at a constant sliding velocity of 1 m/s after a total sliding distance of 2400 m

The coefficient of friction (µ) for the uncoated AISI 309 SS steel is less in general when compared to plasma-sprayed coatings under all normal load conditions. Moreover, the observed variations in µ values are due to several factors, such as intrinsic properties of the materials, operating conditions (temperature and humidity), sliding speed, and applied load. Khruschov (Ref 20) has also suggested that it is difficult to get the exact value of µ. The µ value follows the order as shown below:

$$\text{AISI 309 SS} < \text{Ni-20Cr} < Ni_3Al \quad \text{(Eq 3)}$$

It is interesting to note that the mean values of µ for the uncoated, Ni-20Cr and Ni_3Al-coated AISI 309 SS steel under 50 N normal load are found to be higher than their respective 30 N normal load values. From the ongoing discussion, it can be concluded that the wear resistance of the AISI 309 SS can significantly be improved with the application of plasma-sprayed Ni-20Cr and Ni_3Al coatings.

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5. Conclusions

- The plasma process provides the possibility of deposition of Ni-20Cr and Ni_3Al powders on AISI 309 SS steel. A uniform coating thickness of 100 μm was achieved.
- The wear resistances, as well as, the coefficient of friction values for AISI 309 SS steel, plasma-sprayed Ni-20Cr and Ni_3Al coating followed a general trend irrespective of the value of normal load as given below:

$$\text{AISI 309 SS} < \text{Ni-20Cr} < Ni_3Al.$$

- From the current investigation, the Ni_3Al coating may be recommended as a better choice to reduce the wear of AISI 309 SS steel in comparison with the Ni-20Cr coating.

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