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Performance of Flame Sprayed Ni-WC Coating under Abrasive Wear Conditions

S. Harsha, D.K. Dwivedi, and A. Agarwal

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This paper describes the influence of a post spray heat treatment on the microstructure, microhardness and abrasive wear behavior of the flame sprayed Ni-WC (EWAC 1002 ET) coating deposited on the mild steel. Coatings were deposited by using an oxy-acetylene flame spraying torch (Superjet Eutalloy L & T, India). The wear behavior of the coating was evaluated using a pin on disc wear system against SiC abrasive medium of 120 and 600 grades at 5, 10, 15, and 20 N normal load. Results revealed that the influence of normal load on wear is governed by the microstructure, hardness and abrasive grit size. The heat treatment increased average microhardness of the coating. However, it was found that the hardness does not correctly indicate the abrasive wear resistance of Ni-WC coating in an as sprayed and heat treated condition. The heat treatment of the coating improved its abrasive wear resistance against fine abrasive medium while the wear resistance against coarse abrasive was found to be a function of a normal load. At low-normal load (5 and 10 N) the heat treated coating showed lower-wear rate than as spayed coating while at high-normal loads (15 and 20 N) heat treated coating was subjected to higher-wear rate than as sprayed coating. In general, an increase in normal load increased the wear rate. The scanning electron microscopy study indicated that the wear largely takes place by groove formation and scoring of eutectic matrix and the fragmentation of the carbide particles.

Keywords abrasive wear, flame spraying, microhardness and microstructure, mild steel, Ni-WC coating, normal load, post spray heat treatment

1. Introduction

In the engineering industry, the abrasive wear is probably the most common cause of a mechanical damage. It may appear in several forms such as wear of parts interacting with the abrasive medium, wear by abrasive fluids and wear of the machine parts between which abrasive particles can penetrate (Ref 1). Abrasive wear can be classified as two body or three-body wear and low stress or high-stress abrasive wear depending upon the kind of interaction of abrasive particles and loading conditions. In case of two-body abrasion, abrasive particles simply rub against a surface while in case of three-body abrasion abrasive particle can become trapped between two sliding surfaces (Ref 2-6). Abrasive wear is determined by many material related parameters (bulk hardness, flow, and fracture properties, work hardening and microstructural characteristics apart from the sliding wear conditions (abrasive type and its hardness, abrasive grit size and shape, sliding speed, normal load, nominal area of wear surface and environmental conditions).

The tailoring of the surface properties to meet the service conditions by developing a coating of hard and wear resistant material is an extensively used practice in the industry. Depending on the service conditions coating materials are selected. Common coating materials are cobalt, nickel and iron alloys with varying proportions of hard carbide/boride particles. Ni-WC coatings are extensively used for wear resistance application in order to increase the working life of tribological components subjected to wear (Ref 7-9). High fraction of the carbide particles increases the hardness whereas nickel matrix provides desired toughness. WC particles are hard (1800-2500 VHN) and stable as they do not decompose easily even at elevated temperatures (Ref 7, 8). The hardness of the Ni-WC coating depends on the microstructural parameters such as fraction of soft matrix and type and fraction of carbide particles, size and shape of carbide particles, etc. Recently efforts were made to study the abrasive wear behavior Ni-WC coatings under different test conditions (Ref 2, 7-12). Ghosh et al. (Ref 7) investigated the influence of preheat and post spray heat treat treatment temperatures on the microstructure and dry sliding wear behavior of Ni-WC coating and concluded that the increase in the heat treatment temperature reduces the volume fraction of carbide particles and enhances the hardness and wear resistance of coating. Krishna et al. (Ref 8) investigated the influence of oxygen to fuel ratio in the flame spayed Ni-WC coating and reported that the carbon loss during the spray process in excess of 45% resulted in reduced hardness and wear resistance of the coatings. Coatings with high amount of WC and W_2C particles along with FeW_3C particles showed higher-wear resistance. Coatings of high-wear resistance can be produced using fused tungsten carbide powder with WC and W_2C phases. Skulev et al. (Ref 10) investigated the influence of the heat treatment on the microstructure and mechanical properties of the nickel-base plasma sprayed coatings on steel substrate. They found that the heat treatment above 700 °C enhances the hardness of coating. Tobar et al. (Ref 11)

S. Harsha, D.K. Dwivedi, and **A. Agarwal,** Department of Mechanical & Industrial Engineering, Indian Institute of Technology, Roorkee, 247667, India. Contact e-mail: dkd04fme@iitr.ernet.in.

investigated the influence of WC particles in self-fluxing NiCrBSi alloy clad deposited austenitic stainless steel (AISI: 304) using laser to determine the influence of the volume fraction of the reinforced WC particles on the performance of the composite layer. They reported that the most of clad layer properties such as porosity, microhardness and homogeneity are determined by the percentage of WC particles in the mixture. Kim et al. (Ref 12) investigated the abrasive wear performance of flame sprayed and fused Ni-base alloy coating and found that the coating of 35% WC with NiCrBSiC show the best quality (the highest hardness and the lowest porosity). However, 40% WC addition provided the best wear resistance for dry sand rubber wheel abrasive wear test. The dry sliding wear resistance of the 20% (and or 30%) WC-NiCrBSiC composite coating is almost 10 times better than that of the quenched and tempered JIS SUJ2 bearing steel.

The literature survey did not show many publications on the influence of a post spray heat treatment (PSHT) on the microstructure, microhardness and their wear behavior under reciprocating abrasive wear conditions against fine and coarse grit size abrasives. In the present investigation, an attempt has been made to study the influence of PSHT on the microstructure, microhardness and abrasive wear behavior of the flame sprayed Ni-WC (EWAC 1002 ET) coating against 120 and 600 grade abrasives.

2. Experimental Procedure

2.1 Materials

The chemical compositions of the mild steel substrate and coating used in this investigation are shown in Table 1. Thermal spraying was done on mild steel plate of size $50\times30\times12°mm^3$. Details of the procedure used to develop the coating are shown in Table 2.

Table 1 Chemical composition (wt. %) of substrate and Ni-WC powder

Element	Coating powder	Substrate
C	4.5-6.0	0.2-0.22
Cr	6.5-7.3	...
Ni	Balance	...
W	30-35	...
Si	2.5-4.3	0.4-0.6
Fe	...	Balance
Co	...	...
Mn	0.6-0.72	0.4-0.8

Table 2 Parameters of flame spray process

Sr. no.	Parameters	Quantity
1	Cleaning of substrate using acetone	...
2	The pressure of the oxygen	3 kg/cm^2
3	The pressure of acetylene	1.2 kg/cm^2
4	Torch angle with respect to plate	60°
5	Distance of torch tip from the substrate	20 mm
6	Torch speed	10 cm/min
7	Preheat temperature	300 °C
8	Post spray heat treatment temperature	800 °C

2.2 Metallography

Transverse section of the coating was polished using a standard metallographic procedure which consisted grinding followed by polishing and etching. Polished section of the coating was etched with mixture of HCl (1 cc), HNO_3 (10 cc), H_2O (10 cc). The microstructure of the coating and substrate were studied under optical microscope (Leitz, MM6). The scanning electron microscopy (Leo-435-VP-England) of the worn out surfaces was carried out to study the wear mechanism. The microhardness (VHN) of base metal, coating and interface was tested at constant load of 100 g.

2.3 Wear Test

The wear behavior of the flame sprayed coatings was studied using a pin-on-flat type wear testing unit (Fig. 1). Coated wear pin of size $5\times5\times20$ mm^3 was held against an abrasive medium during the wear test. Water proof SiC abrasive papers of 120 and 600 grade were used as an abrasive medium. Abrasive paper of 120 and 600 mesh sizes corresponded to average grit of size about 135 and 30 μm respectively. Abrasive paper was mounted on the reciprocating steel plate ($100\times50\times10$ mm^3), which was reciprocated at an average speed of 0.2 m/s sliding speed. Wear pin was moved cross-wise on an abrasive medium after each cycle of forward and backward movement to make the fresh abrasives available for the abrasion. Sliding period for each test was 10 min. The wear tests were conducted under four normal loads, i.e., 5, 10, 15, and 20 N. A Mettler microbalance (accuracy 0.0001 g) was used for weighing the specimens before and after the sliding. The weight loss was used as a measure of wear. Wear rate was calculated using weight loss per unit of sliding distance. The wear pins were cleaned with acetone prior to and after the wear test.

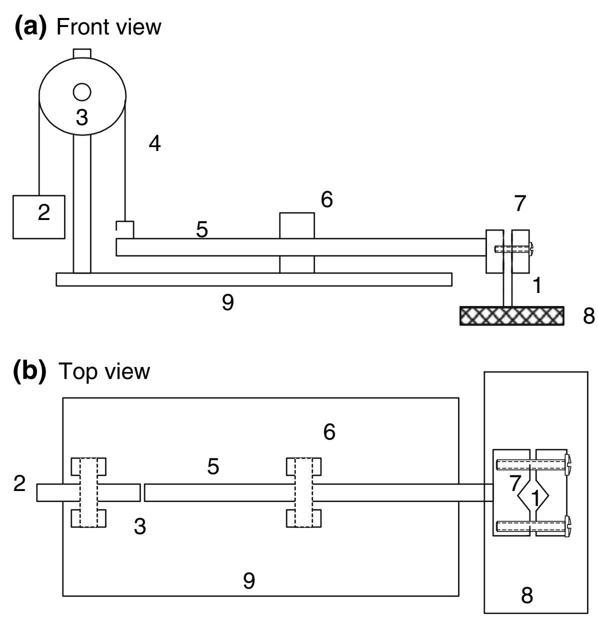

Fig. 1 Schematic diagram of pin on plate wear test machine (1 wear pin, 2 weight, 3 pulley, 4 string, 5 lever arm, 6 fulcrum of lever, 7 wear pin holder, 8 reciprocating counter surface affixed with abrasive medium and 9 base plate); (a) Front view and (b) Top view

3. Results and Discussion

3.1 Microstructure

The microstructures of the steel substrate and coating in as sprayed and heat-treated condition are shown in Fig. 2-4. Optical micrograph (Fig. 2) of the steel substrate mainly exhibits two microconstituents, i.e., ferrite and pearlite. Microstructure of as sprayed (nonheat treated) Ni-WC coating is shown in Fig. 3(a, b). It is important to mention that this micrograph was taken from a region near the interface. As sprayed coating (Fig. 3a) primarily exhibits two microconstituents namely primary WC particles of polyhedral shape (A) and eutectic-carbides (B). It can be seen that the cuboid shape primary carbide particles (bright area) are present in the matrix of eutectic (dark zone) which is probably composed of nickel and eutectic M_7C_3 carbide. Fraction of eutectic near the interface is approximately 70.2% whereas that of the primary carbide particles is about 22.6%. Average size of carbide particles is 26 μm. Further, it is observed that a band of black zone is formed near interface in the substrate. This kind of band has also been reported earlier (Ref 7) and it was attributed to segregation of carbon near interface. The porosity can be seen in the coating and it is about 7.2%. The microstructure of an as sprayed (nonheat treated) Ni-WC coating away from the interface is shown in Fig. 3(b). This micrograph is also exhibiting two microconstituents namely primary carbides of polyhedral shape (bright area) and eutectic (dark area). In this micrograph fraction of eutectic is approximately 37.3% whereas that of primary carbide is about 47.6%. Average size of the carbide particles is 30 μm. These micrographs clearly show that fraction of carbide particle in the coating away from the interface (Fig. 3a) is more than that near interface (Fig. 3b).

Microstructure of a heat-treated Ni-WC coating is shown in Fig. 3(c, d). These micrographs were taken from both the central region of the coating and the interface. The heat-treated coating exhibited slightly different microstructure at interface

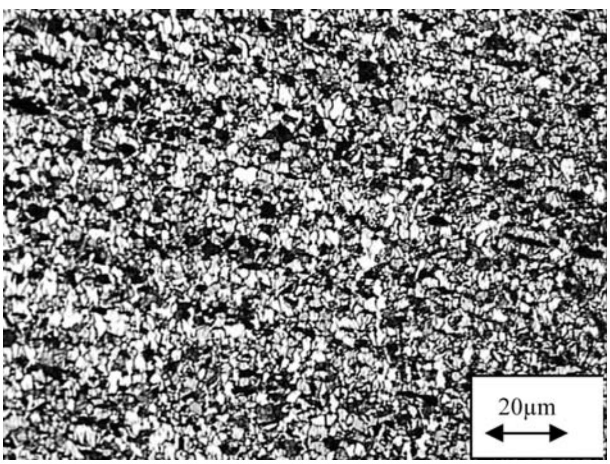

Fig. 2 Typical microstructure of substrate

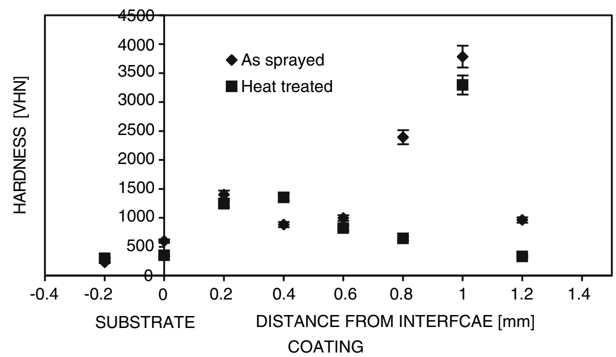

Fig. 4 Influence of heat treatment on Vickers hardness

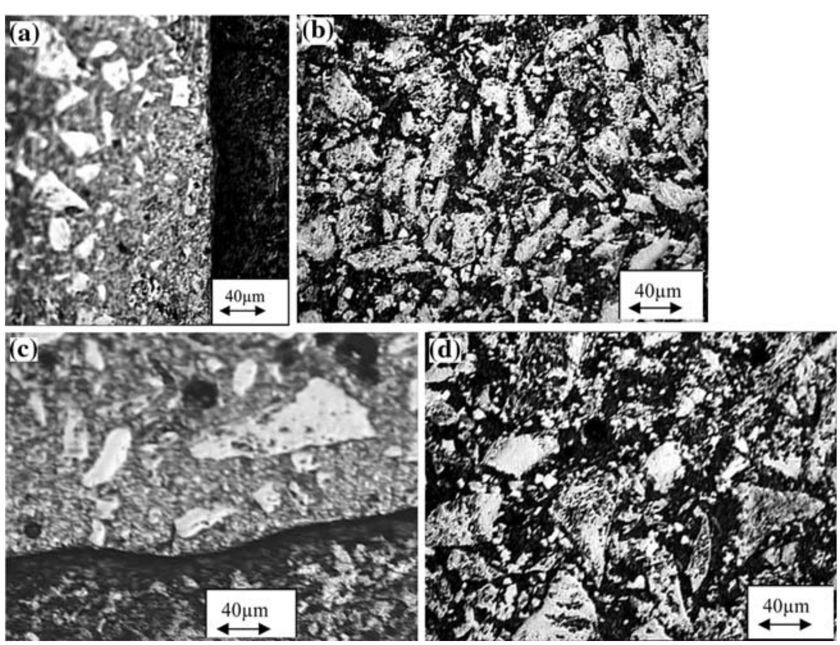

Fig. 3 Optical micrograph of (a) coating-substrate interface in as sprayed condition, (b) center region of coating in as sprayed conditions, (c) coating-substrate interface in heat treated condition, and (d) center region of coating in heat treated condition

compared to central zone of the coating. The heat-treated coating near the interface (Fig. 3c) showed lesser fraction of the primary carbides than that in central region of the coating as shown in Fig. 3d. Fraction of eutectic in heat-treated coating near the interface is approximately 72.8% whereas that of polyhedral shape and other fine carbide particles is only about 18.4%. Size and fraction of the carbide particles increased with the distance from the coating-substrate interface. Average size of carbide particles in the heat-treated coating near the interface was 32 μm. Porosity near the interface is about 9.2%. Micrograph of coating in the center region (Fig. 3d) exhibits mainly two microconstituents viz. primary cuboid shape carbide particles in the matrix of eutectic which solidified in last. It is evident that the fraction and size of carbide particles is larger at some distance from the interface compared to near the interface region. Fraction of the carbide particles in the heat-treated coating away from the interface was 38.5% whereas eutectic was found about 48.2%. The difference in ratio of these phases may be attributed to varying composition and cooling conditions across the coating thickness. Variation in fraction of carbide particles can appreciably affect the hardness and therefore abrasive wear resistance of coating. Further, it is expected that high-temperature exposure during the heat treatment would promote the solid state transformation leading to the formation of carbides and intermetallic compounds.

3.2 Microhardness

The microhardness of the coating in an as sprayed and heat-treated condition of Ni-WC coating was measured following the standard procedure on Vickers scale using 100 g load. Variation in the hardness with distance from the interface toward the coating in a heat treated and as sprayed condition is shown in Fig. 4. Large scatter in values of the hardness is due to the presence of the hard carbide particles in the comparatively soft matrix. The substrate-coating interface showed lower hardness values than the coating. Non-heat-treated coatings were found comparatively softer than the heat-treated coating. With the increase in distance from the interface to the coating side showed increase in the hardness and after reaching to a peak value it decreased. Hardness of carbide particle in as spayed condition was found in a range of 2394-3700 VHN whereas that of eutectic was in range of 599-1402 VHN. Hardness of carbide particle in heat-treated condition was found in a range of 2610-3296 VHN while that of the eutectic was in a range of 642-1353 VHN. The results showed that the scatter in the hardness was more in an as sprayed condition than heat-treated condition. Probably, homogenization of the composition and precipitation of the fine carbide particles after the heat-treatment reduced dispersion in the hardness values. An increase in the hardness with distance from the interface has also been reported earlier (Ref 7). Ghosh et al. (Ref 7) reported that PSHT increases the hardness of the coating and peak hardness lies somewhere between the substrate-coating interface and coating surface.

Increase in the hardness of the eutectic may be attributed to the precipitation of fine WC particles in the eutectic matrix. It was observed that the hardness of eutectic and carbide particles increased with the distance from interface. The variation in microhardness is probably due to local differences in phase and chemical composition. The heat treatment has been reported to improve the mechanical properties of coating (Ref 10). Low hardness near the interface can be attributed to less fraction of carbide particle than away from interface. Ghosh et al. (Ref 7) attributed the low hardness near the interface to less availability of carbon due to their diffusion to mild steel substrate near the interface. Low hardness near the surface of the coating may have been due to oxidation of carbon and WC and W_2C above 565 °C and WO_3 formation.

3.3 Abrasive wear Behavior

Abrasive wear behavior of Ni-WC coating in as sprayed and heat-treated condition as a function of normal load against two different abrasive mediums is shown in Fig. 5(a, b). In general, an increase in the normal load increases the wear rate (g/km) of the coating both in as sprayed and heat-treated condition.

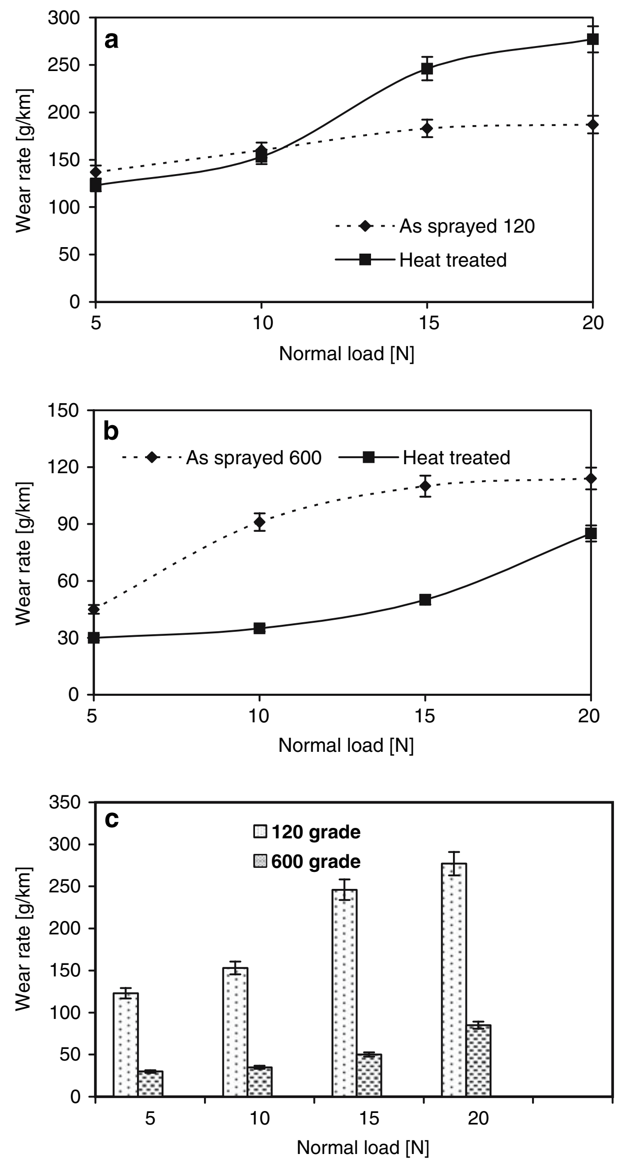

Fig. 5 Influence of heat treatment on wear behavior (a) wear rate vs. normal load relation for coating in as sprayed and heat treated conditons against 120 grade abrasive medium, (b) wear rate vs. normal load relation for coating in as sprayed and heat treated conditons against 600 grade abrasive medium and (c) comparative wear rate vs. normal load relationship of heat treated coating against different abrasive medium

Further, the influence of load on the wear rate in an as spayed and heat-treated condition against fine and coarse abrasive medium was quite different. It can be seen from the Fig. 5(a) that the heat treatment of Ni-WC coating deteriorates the wear resistance against coarse abrasive (low grade) especially at high loads as these coatings in the heat-treated condition are subjected to higher-wear rate than in as sprayed condition. Wear rate of the heat-treated coating increases rapidly with an increase in the normal load above 10 N while the wear rate of as spayed coating increases gradually with an increase in the normal load from 5 to 20 N.

The heat treated Ni-WC coating showed better wear resistance against the fine abrasive medium (600 grade) also as these were subjected to lower-wear rate than as sprayed coatings (Fig. 5b). A careful observation of Fig. 5(a, b) showed that coating in as spayed condition is subjected to higher-wear rate against coarse abrasives (low grade) than fine abrasives at constant load. It has been reported that the wear resistance of WC based coatings is greatly improved if the tungsten carbide fuses and forms W_2C during the spraying. Influence of abrasive medium on wear behavior of heat-treated coating is shown in Fig. 5(c). It can be seen that the wear rate of coating against 120 grade abrasive is about 2-3 time greater than that against fine 600 grade abrasive. Fused tungsten carbide consists of two phases, i.e., WC and W_2C. W_2C is harder phases than WC. Therefore, the microstructure and properties of coating not only depend on the composition of spraying powder but also on the phase transformation taking place during the spray process. Kim et al. (Ref 13) reported that the size of carbides and fraction of carbides are more crucial factor than hardness. However, extent of influence depends on size of abrasive particles.

3.4 Scanning Electron Microscopy

Wear surface of the coating in both as spayed and heat-treated condition revealed general surface morphologies such as microfatigue, scratches, fragmentation and microcracking. Scanning electron microscopy image (Fig. 6a) shows the sub-surface features generated during the sliding. Micrograph reveals both worn out surface (A) and as sprayed surface (B). It can be seen that the wear surface clearly reveal carbide particle in the matrix of eutectic whereas un-worn is irregular and microconstituents could not be seen. Scanning electron microscopy image wear surface as spayed coating under 5 N load and 120 grade, exhibits the mechanism of wear active in these coatings. It can be seen that there are deep scratches in the eutectic matrix running in the direction of sliding. It is evident that growth of these scratches in matrix is discontinued by the presence of hard carbide particles. Probably hard tungsten carbide particle obstructs the propagation of scratches due to abrasive action during the sliding. Scratches can be seen in both eutectic matrix and hard carbide particles. Depth of these grooves is very shallow compared to that in eutectic matrix. However, plastic deformation of matrix as extruded fins at the edge of grooves was not visible. Further, loss of materials from the wear surface can also be there by gradual removal of hard carbide during the abrasion process. It is evident that the loss of these carbide particles takes place by fragmentation even when these are well supported by the matrix. Fragmentation of carbide and their spalling has also been reported earlier by Krishna et al. (Ref 8).

4. Discussions

As reported earlier pre-requisite for abrasive wear is an indentation caused by hard abrasive particle (Ref 4). Relative motion of hard particles with respect to a mating surface is known to produce scratches on the softer surface. Dimension of these scratches (length, width, and depth) determines the loss of material from the wear surface. These dimensions are governed by the abrasive wear parameters and material characteristics (Ref 3, 4). Wear test parameters such as size and shape of abrasive, hardness of abrasive particles, relative speed between abrasive and wear surface, normal load. Material parameters such as hardness, ductility, flow stress, brittleness, work hardening characteristics and their microstructural aspects (size, shape, distribution of various phases and their relative amounts) are important from wear point of view. Depending upon the plastic flow characteristics of a wear surface material, scratch being formed by abrasive action may or may not cause the wear. Soft and ductile materials tend to flow side wise (perpendicular to the direction of sliding). This side wise flow produces ridges on both sides of groove without must loss of materials. This phenomenon has been termed as plowing in literature. Hard and brittle coating materials do not deform to a large extent to form these ridges. Further, brittle and hard coating material generally develops crack under the influence of stress during the sliding. Coalescence of these cracks might produce small metallic pieces as wear debris.

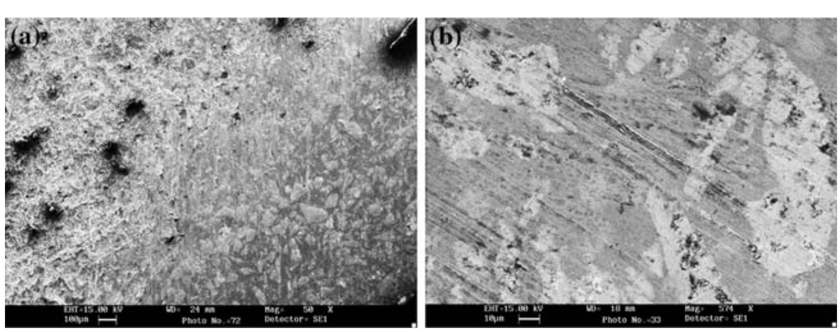

Fig. 6 Scanning electron microscopy images of wear surface of coating tested against 120 grade abrasive medium at 5 N normal load (a) showing zones of wear surface and as sprayed un-worn surface of coating at low magnifications and (b) closer look of wear surface showing the deep scratches on eutectic matrix and areas from where probably carbide particles have been removed gradually by fragmentation

Depth of scratches depends on normal load and hardness. High load and low-indentation hardness of material, increases depth of scratches which in turn would increase wear rate. Width of scratch is determined by normal load and size of abrasive particles. Coarse abrasive and high load would produce wider scratch. Length of scratch is controlled by the metallurgical parameters such as fraction of second phase hard particle, mean free path, hardness and size of these particles. If second phase carbide particles are harder than abrasive then these particles are not easily abraded and so tend to break the continuity of scratches. This is evident from scanning electron microscopy image of wear surface (Fig. 6b). It can be seen that soft matrix has been scratched and their continuity is broken by the presence of hard WC particles.

Influence of second phase hard particles on wear appears to be a function of both load and abrasive grit size probably because these factors determine the depth of penetration. Present study on wear rate vs. load relationship of Ni-WC coating against coarse abrasives (120 grade) showed that wear rate of heat-treated coating is lower than as sprayed coating only under light load (5 and 10 N) condition while under higher loads (15 and 20 N) heat-treated coating was subjected to higher-wear rate compared to as sprayed coating. This is probably due to precipitation of the fine carbides in eutectic matrix during the heat treatment which could not be seen under low magnifications. It may be attributed to the fact that during the thermal spraying owing to high temperature (3100 °C is common with oxy-acetylene flame) tungsten carbide particle may get transformed into W and W_2C. Elemental W can precipitate as fine WC particles in the matrix during the PSHT because of high affinity with carbon, which in turn would appreciably increase the hardness of coating. During the post heat treatment W_2C may get transform into WC by consuming free carbon if available either in matrix or carbide particles (Ref 7). These fine carbide particles would contribute effectively to reduce the abrasion of soft matrix at light load when depth of indentation is not very large. It has been reported that hard phase are effective as discrete components of the structure only when their size is same or larger than the wear debris formed during the abrasion, if they have to obstruct scratching by abrasives (Ref 1). Under light load condition it would not be wrong to speculate that size of wear debris particles should be small than the high-normal load.

At high loads, when large size debris are produced owing to greater depth of penetration by coarse abrasive, only large hard second phase particles might prevent the scratching of matrix. It may lead to higher-wear rate of heat-treated coatings than as sprayed coatings under high load conditions. Further, the microstructure study results also support to the above phenomenon because as sprayed coating (Fig. 3a, b) showed higher fraction of large carbide particles than heat-treated coating (Fig. 3c, d).

Lower-wear rate of heat-treated coating at different loads against the fine abrasives (600 grade) than as sprayed coating may be attributed to precipitation of fine carbide particles in the eutectic matrix. However, micrograph revealed that fraction of coarse particles reduced after heat treatment. It can be concluded that heat treatment of Ni-WC coating improves the wear resistance only when depth of indentation is not significant (light load, fine abrasives).

Higher-abrasive wear rate of heat treated coating against the coarse abrasives (120 grade) at higher load may be attributed to increased proportion of soft eutectic matrix compared to that in as sprayed conditions. Ghosh et al. (Ref 7) have also reported that PSHT show a tendency to lower the amount of carbide particle and their area fraction (45-32%) in matrix and it was attributed to solutionizing some of the carbide particles in the matrix. Probably these particles are removed by large abrasive particles. Comparatively soft eutectic matrix might be easily abraded by hard SiC abrasives which eventually lead to pulling off hard carbide particles from the matrix due to lack of support. Increased depth of indentation by large abrasive particles would be removing larger volume of material from the wear surface (Fig. 6b).

Metallurgical structure such as grain size, dispersed phases, lamellae, etc. have considerable influence on the mechanical properties of materials and therefore, since abrasive wear involves plastic flow, must also influence abrasive wear resistance. Generally, abrasive wear resistance is improved by hard carbide particles in soft matrix in the following ways: increase in carbide (M_7C_3) particles size, small ratio of groove size of abrasive to carbide size, smaller mean free path, high-volume fraction of carbide particles, low-interface energy between the carbide particles and matrix (Ref 1).

It is suggested that low-wear rate against the fine abrasives may be due to two factors (1) low-indentation depth under a given load and (2) clogging and blunting tendency of fine abrasives by the material removed from the wear surface.

5. Summary

1. Microstructure of the coating showed large polyhedral shape primary WC carbide particles in the matrix of eutectic. Significant variation in fraction of carbide particles near the interface and that away from interface was observed. Heat treatment reduced the fraction of primary carbide particles and increased the area fraction of eutectic matrix.
2. The microhardness of Ni-WC coating varies across the interface. Peak microhardness was found in between the interface and coating surface. Heat-treated coating showed marginal improvement in microhardness than as sprayed coating.
3. Increase in wear rate due to increase in normal load has been found a function of abrasive grit size and coating condition. PSHT of coating showed better wear resistance against fine grit size abrasive (600 grade). Heat treatment also showed marginal improvement against coarse abrasives below 10 N normal load. Further, the wear resistance under high-normal loads was somewhat lower against coarse abrasive (120 grade) than as sprayed coating.
4. Loss of material from the wear surface of the coating takes place primarily by removal of soft matrix materials followed by fragmentation of hard carbide particles as scanning electron microscopic study exhibited deep abrasive marks only in eutectic matrix.

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