JMEPEG (2002) 11:37-45

High Stress Abrasive Wear Behavior of Some Hardfaced Surfaces Produced by Thermal Spraying

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(Submitted 22 November 2000; in revised form 2 July 2001)

Steel surfaces were thermally sprayed with nickel chromium boron (NCB) powder (with and without tungsten carbide) using an oxy-acetylene torch. The sprayed (hard) surfaces and substrate were characterized for abrasive wear properties. Test parameters such as load and sliding distance were varied. A significant improvement in the abrasive wear resistance (inverse of wear rate) was noted for the thermally sprayed surfaces as compared to that of the substrate. Wear surfaces, subsurface regions, and debris were examined in order to ascertain the operating wear mechanisms. Substrate (mild steel), because of its low hardness, suffered severe wear through the cutting, ploughing, and wedging action of the hard abrasive (silicon carbide). Deep cuts on the worn surface, a bulky transfer layer, subsurface cracks, and large-size debris were observed. However, wear was reduced due to high hardness of the layer of NCB powder on the substrate, which resisted the penetration of abrasive into the surface. Presence of tungsten carbide in the layer of NCB powder further reduced the wear of the corresponding specimen because of very high hardness of the tungsten carbide. Shallow wear grooves and finer debris were observed for the NCB coating with and without tungsten carbide. Cutting was the predominating wear mechanism in the case of coatings.

Keywords abrasive wear, hardfacing, property improvement, surface modification

1. Introduction

Surface modification is an emerging technique through which various properties of materials can be improved to a great extent.[1,2] Among many techniques of surface modification, thermal spraying is very attractive because of its relatively simpler operation and flexibility in the selection of coating powder with respect to requirements of applications.[3] In this technique, thermal energy is used to spray metal and ceramic powders to form a dense coating on the prepared surface of substrates. A wide range of coating materials such as aluminum, bronze, steel, nickel and its alloys, and ceramic powders may be deposited by thermal spraying technique with 95% efficiency.[4] Its application includes deposition of corrosion, abrasion, and wear-resistant coatings/layers on large and intricately shaped surfaces. About 75% of the hardfacing alloys are iron based.[5] However, nonferrous hardfacing alloys having high melting points are also used in environments that are too aggressive for the ferrous hardfacing alloys to withstand, or where high resistance to specific types of wear is required.[5] Chemical processing, power, automotive, and oil industries require resistance to a hostile environment in addition to resistance to wear. Nonferrous hardfacing alloys are used in such applications. Furthermore, ceramic coatings are attractive for wear-resistant applications because of their high hardness, but brittleness limits their usefulness in some of the wear applications.[6] From a scientific standpoint, materials with excellent wear resistance should possess a combination of high hardness and toughness. Cermets have been developed to offer benefits in terms of hardness of the ceramic and toughness of metals. Tungsten carbide is one of the hard ceramics dispersed in a ductile metallic matrix for wear resistance applications.[7,8]

The objective of the present investigation was to access the extent of improvement in the wear resistance of the steel substrate attainable through surface modification with hard nickel chromium boron (NCB) coatings. In the present study, NCB powder (with and without tungsten carbide) was thermally sprayed on a steel substrate using oxy-acetylene flame. Two-body abrasion tests were carried out on the specimens at various loads for different sliding distances. Wear rate of the specimens was computed by weight loss method. Scanning electron microscopic study was carried out to examine the wear surface,

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Table 1 Chemical Composition of the Substrate and Powders

	Chemical Composition (wt.%, Element)						
Material	C	Si	Mn	Cr	Ni	Fe	B
NCB powder (without WC)	0.78	4.11	—	17.69	Remainder	4.24	3.11
NCB powder (with WC)	NCB powder of above composition containing 50 wt.% WC powder						
Substrate	0.16	0.11	0.40	—	—	Remainder	—

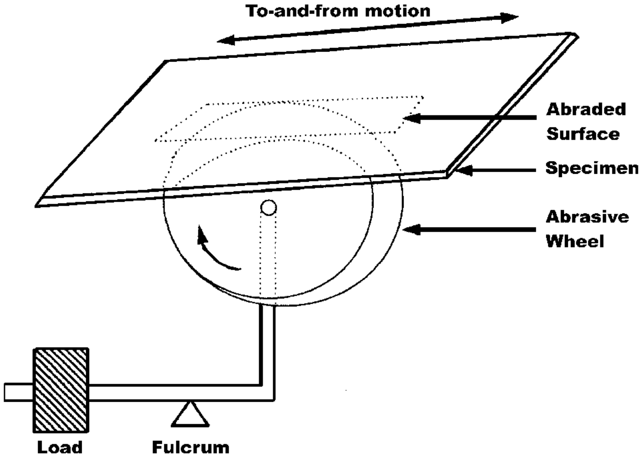

Fig. 1 A schematic diagram of the abrasion test apparatus

subsurface, and debris to elucidate the operating wear mechanisms.

2. Experimental

2.1 Material

Mild steel plates (~4 mm thick) were cut in the form of 35 mm × 40 mm rectangular pieces and their surfaces were prepared by polishing metallographically and cleaning thoroughly with acetone. Oxy-acetylene flame was used to spray the powder on the substrate surface. Coating was carried out manually by maintaining a gun-to-substrate distance of ~22 cm and powder feed rate of ~50 g/min. Chemical composition of the powder and substrate materials is listed in Table 1.

2.2 Wear Tests

High-stress abrasive wear tests were conducted on 35 mm × 40 mm × 4 mm specimens using abrasion test equipment (Suga, Japan). A schematic diagram of the test apparatus is shown in Fig. 1. The test procedure facilitated to-and-fro motion of the specimen against the abrasive medium firmly mounted on a wheel. The specimen was loaded against the abrasive medium with the help of a cantilever mechanism. After each stroke, the abrasive (wheel) rotated slightly in order to offer fresh abrasive surfaces in each stroke. After 400 strokes (i.e., to-and-fro cycles of the specimen), the abrasive reached the initial position. This corresponded to a sliding distance of 26 m traversed by the specimen. Weight loss method was used to calculate the wear rate. Tests were conducted (1) over a sliding distance of 78 m at 1, 3, 5, and 7 N loads using fresh abrasive (i.e., the abrasive was changed after the traversal of 26 m distance every time); (2) over sliding distances of 26, 52, 78, and 104 m at 7 N load using fresh abrasive (i.e., the abrasive was changed as in item 1); and (3) over sliding distances of 26, 52, 78, and 104 m using the same abrasive over the entire range of sliding distances.

2.3 Microstructural Studies

Cross sections of the coated surfaces and subsurface regions of typical tested samples were observed using scanning electron microscopy. Specimens were cut using a slow-speed diamond cutter and mounted in polyester resin. The samples for the observations of subsurface regions were polished and etched as per standard metallographic practices. Wear surfaces, subsurface regions, debris, and abrasive papers were also examined under a JEOL 5600 CF scanning electron microscope (Tokyo, Japan). Specimens were sputtered with gold prior to their SEM study.

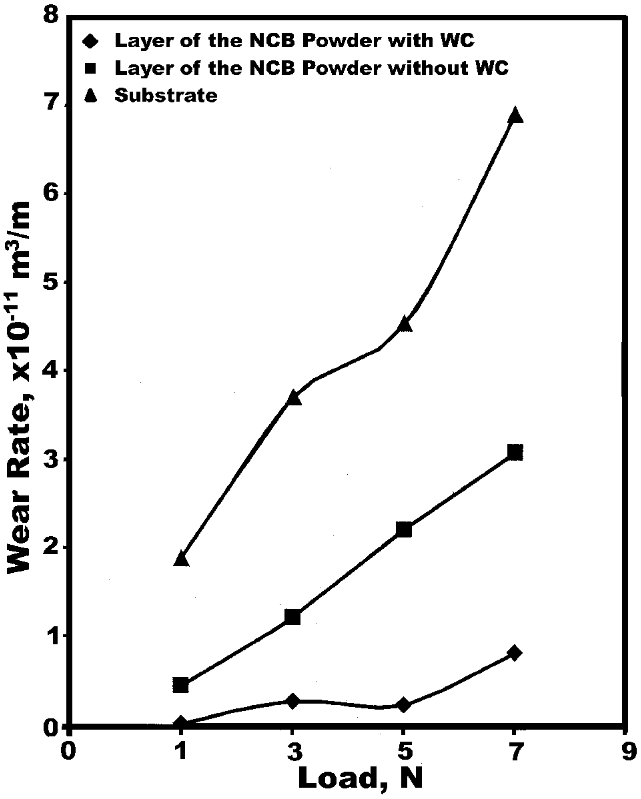

Fig. 2 Wear rate plotted as a function of applied load at a typical sliding distance of 78 m using fresh abrasive (◆, layer of the NCB powder with WC; ■, layer of the NCB powder without WC; ▲, substrate)

2.4 Roughness Measurement

Roughness of the samples prior to and after testing (at 7 N load and over 78 m distance, parallel and perpendicular to the sliding direction) was measured using an RTH-6 profilometer (Rank Taylor Hobson, Leicester, London, U.K.).

3. Results

3.1 Wear Response

Figure 2 shows the variation in wear rate of the specimens as a function of applied load. The abrasive was fresh in this case and tests were conducted over a fixed sliding distance of 78 m. Wear rate increased with increasing load. Maximum wear rate was observed for the substrate specimen followed by that of the layer of the NCB powder without WC; the layer of the NCB powder with WC attained minimum wear rate. There

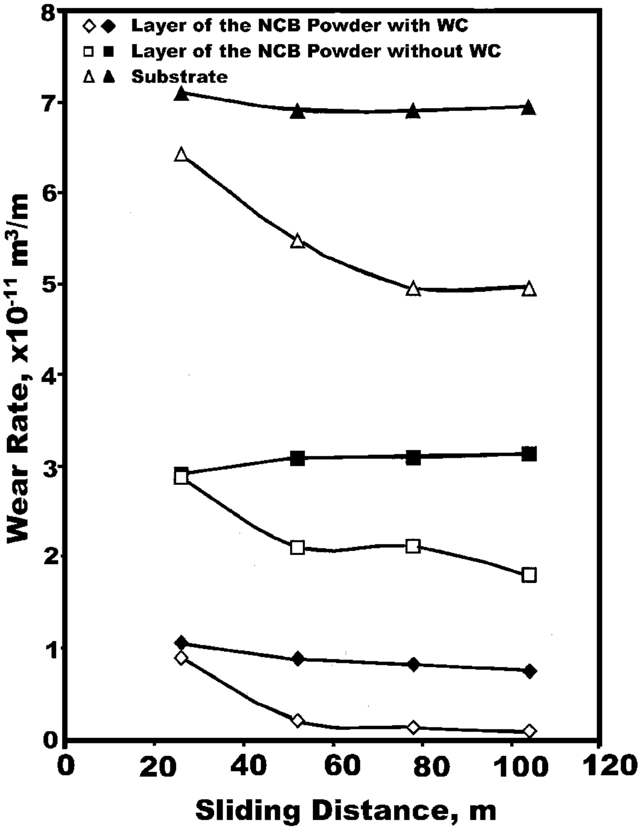

Fig. 3 Wear rate of the specimens plotted as a function of sliding distance at a typical applied load of 7 N using fresh and degraded abrasive over the entire range of sliding distance (◇ ◆, layer of the NCB powder with WC; □■, layer of the NCB powder without WC; △▲, substrate; open symbols, unchanged (degraded) abrasive; closed symbols, fresh abrasive)

was a sharp increase in the wear rate of the steel substrate and the layer of the WC-free NCB powder with load. However, increase in the wear rate with load was comparatively less in the case of the layer of the NCB powder containing WC.

Wear rate of the specimens with sliding distance is shown in Fig. 3. The wear rate reduced with sliding distance in general. However, the extent of reduction in wear rate (with distance) increased when the abrasive remained unchanged (degraded) compared to that using fresh abrasive. It may also be noted that the degree of reduction in wear rate in the case of unchanged (degraded) abrasive over the one with fresh abrasive became greater for the substrate than either of the deposited layers of the NCB powder with and without WC.

3.2 Microstructural Study

Figure 4 shows the microstructure of the samples. The thickness of the layer deposited with the NCB powder containing WC and the one without WC on the substrate was ~150 and 350 μm, respectively (Fig. 4a and b, respectively). The layer of the NCB powder without WC shows complex chromium carbide in the matrix of nickel (Fig. 4c, region A). Similar features were observed in the case of the layer/deposit of the NCB powder with WC, except that the presence of tungsten carbide particles was also seen in the matrix (Fig. 4a). The size of tungsten carbide particles was ~50 μm (Fig. 4a). The microstructure of the substrate steel comprised pearlite plus ferrite (Fig. 4d).

3.3 Wear Surface

Figure 5 shows the SEM micrographs of the worn surfaces of the samples. The sample sprayed with the layer of the NCB powder containing WC revealed a large number of WC particles on the wear surfaces. Continuous and shallow abrasion grooves can also be seen in this case (Fig. 5a). No groove formation took place on the tungsten carbide particles (Fig. 5b). The severity of damage increased for the sample with the layer of WC-free NCB powder (Fig. 5c and d) as compared to the one with WC (Fig. 5a and b). Damaged areas containing pits were also prominent in the WC-free NCB powder coating (Fig. 5d). Worn surfaces of the steel substrate delineated continuous and deeper grooves on the wear surface (Fig. 5e) as compared to those deposited with the layers of the NCB powder with and without WC (Fig. 5a and c). Large surface damage is also evident in the worn surface of the steel substrate (Fig. 5f).

3.4 Subsurface Regions

Microstructures of the subsurface regions of the worn surfaces of the samples are shown in Fig. 6. Microstructural changes in the subsurface regions were observed to be marginal for the layer of NCB powder with WC particles (Fig. 6a). Furthermore, regions close to the wear surface generally appeared to be featureless (Fig. 6a, region A) with the limited presence of fragmented microconstituents (Fig. 6b, region B). The presence of microcracks in the subsurface regions was also observed (Fig. 6b, region marked with arrow). Similar features were also noticed for the layer of the NCB powder without WC (Fig. 6c and d). The subsurface regions of the samples of the layer of the NCB powder with and without WC revealed a negligible amount of adhered mass to the bulk (Fig. 6a and c). Conversely, the adhered mass was considerably large for the substrate (Fig. 6e). A ferrite-pearlite colony could not be seen in the transferred layer, whereas it was observed in the bulk (Fig. 6e, regions C and D, respectively).

3.5 Abrasive Medium

Figure 7 shows the abrasive medium prior to and after testing the specimens. The fresh abrasive medium contained abrasive particles well embedded with the base (Fig. 7a). Protrusion of the intact particles may also be noted in this case (Fig. 7a). Sticking of debris particles on the abrasive medium was observed after testing the samples (Fig. 7b to e). The extent of debris sticking was minimum for the layer of the NCB powder containing WC (Fig. 7b). This was followed by that of the WC-free NCB powder layer (Fig. 7c); the degree of debris sticking was maximum in the case of abrasion of the substrate (Fig. 7d). A magnified view clearly shows that the debris contains flakes and machining chips (Fig. 7e, regions A and B, respectively). Damage to the abrasive particles in the form of fracturing/fragmentation and partial removal during abrasion of the samples was also noted (Fig. 7c and d, regions marked by single and double arrow, respectively).

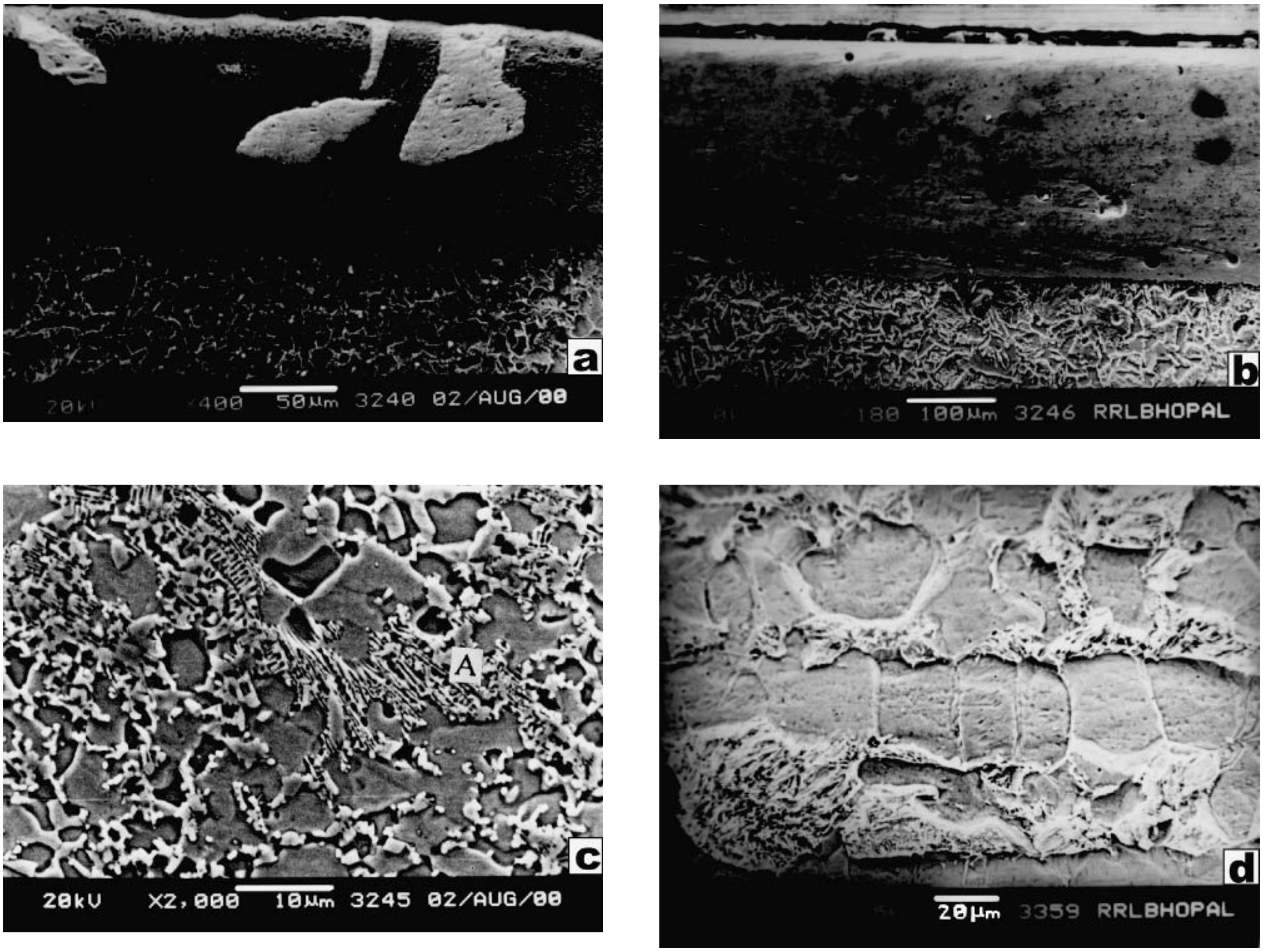

Fig. 4 Microstructure of the transverse section of the sample deposited with the layer of (a) NCB powder with WC particles, (b and c) NCB powder without WC, and (d) substrate

Table 2 Roughness (R_a) Values of Specimens (µm)

	Roughness Measurement with Respect to Sliding Direction	Substrate	Layer of NCB Powder (Without WC)	Layer of NCB Powder (Containing WC)
Before wear		0.125	0.134	0.554
After wear at load: 7 N, distance: 78 m	Parallel	0.226	0.247	0.324
	Perpendicular	0.669	0.650	0.466

3.6 Roughness Measurement

The surface roughness increased after wear at 7 N load for 78 m distance of the substrate and layer of the NCB powder without WC, whereas the trend reversed for the layer of the NCB powder containing WC (Table 2).

4. Discussion

In the present study, abrasion resistance of substrate material could be increased by depositing NCB powder with and without tungsten carbide particles. In general, abrasive wear properties of this group of alloys depend on their carbon and boron contents.[5] Chromium, boron, and carbon contents together with that of nickel determine the level and type of hard phases formed therein. Boron is the main hard phase forming element, whereas carbon is the secondary hard phase former.[5] Silicon facilitates the formation of intermetallic compounds such as Ni_3Si,[5] and thus considerably influences the wear properties of the alloys. In the presently used alloy system, dominant hard phases such as Ni_3B and chromium boride (normally CrB, and occasionally Cr_2B and Cr_3B_2) are formed along with the complex carbides of $M_{23}C_6$ and M_7C_3 types.[5]

Wear rate of the layers of the NCB powder with and without

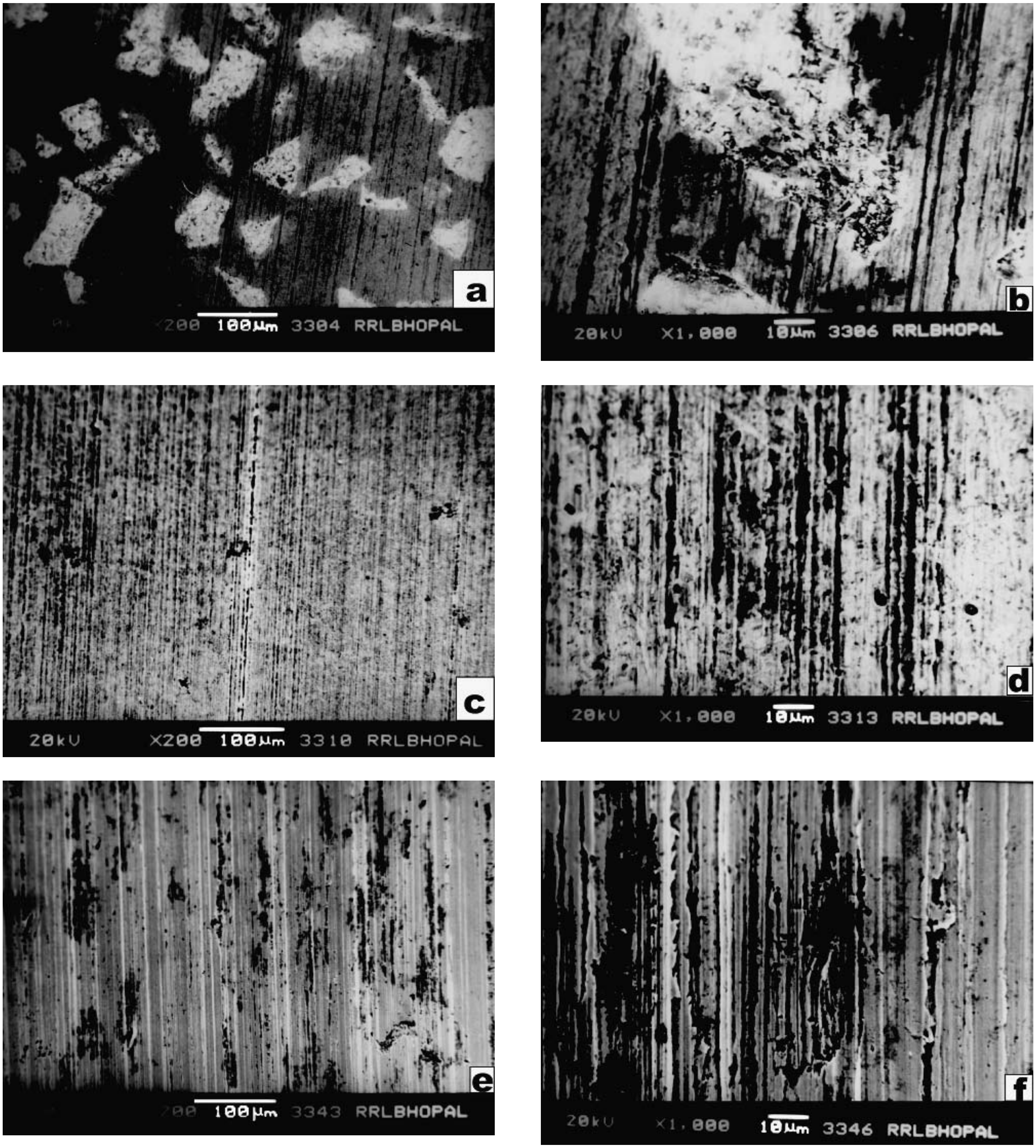

Fig. 5 Abraded surfaces of (a and b) the layer of NCB powder with WC, (c and d) layer of NCB powder without WC, and (e and f) substrate tested over a sliding distance of 78 m at a load of 7 N using fresh abrasive

WC was significantly lower than that of the substrate, i.e., mild steel (Fig. 2 and 3), due to the presence of hard microconstituents such as complex carbides, nickel boride, and WC in the former case (Fig. 4a to c); the phases offer high hardness. For the layer of the NCB powder without WC, wear rate decreased because of the presence of complex carbide and boride phases, whereas tungsten carbide further improved the wear properties because of its higher hardness in the case of the layer of the NCB powder containing WC. The view is substantiated through the higher hardness of the layer of the NCB powder

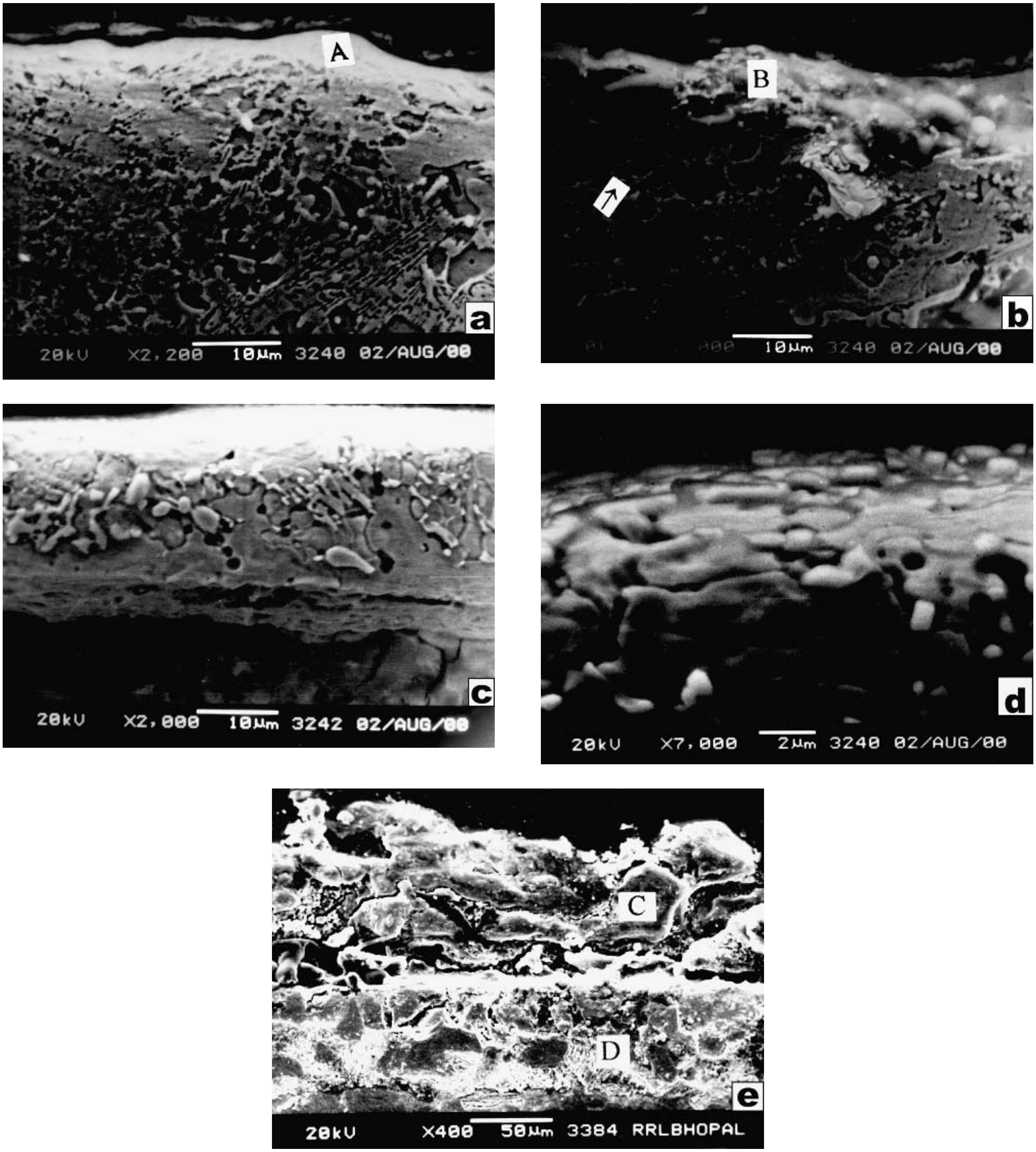

Fig. 6 Subsurface regions of (a and b) the layer of NCB powder with WC, (c and d) the layer of NCB powder without WC, and (e) the substrate tested over a sliding distance of 78 m at a load of 7 N using fresh abrasive. (A, featureless region; B, fragmented microconstituents; arrow, microcracks; C, absence of ferrite-pearlite colony; D, ferrite-pearlite colony)

with and without WC (the hardness being ~875 and ~700 HV, respectively) than that of the substrate (245 HV); hardness of WC particles was found to be 2373 HV.

Available information suggests that microstructural parameters such as size, shape, volume fraction, hardness, and distribution of hard phases in the matrix are the factors responsible for specific abrasive wear properties of materials consisting of soft and hard phases.[9-14] Furthermore, relative hardness and

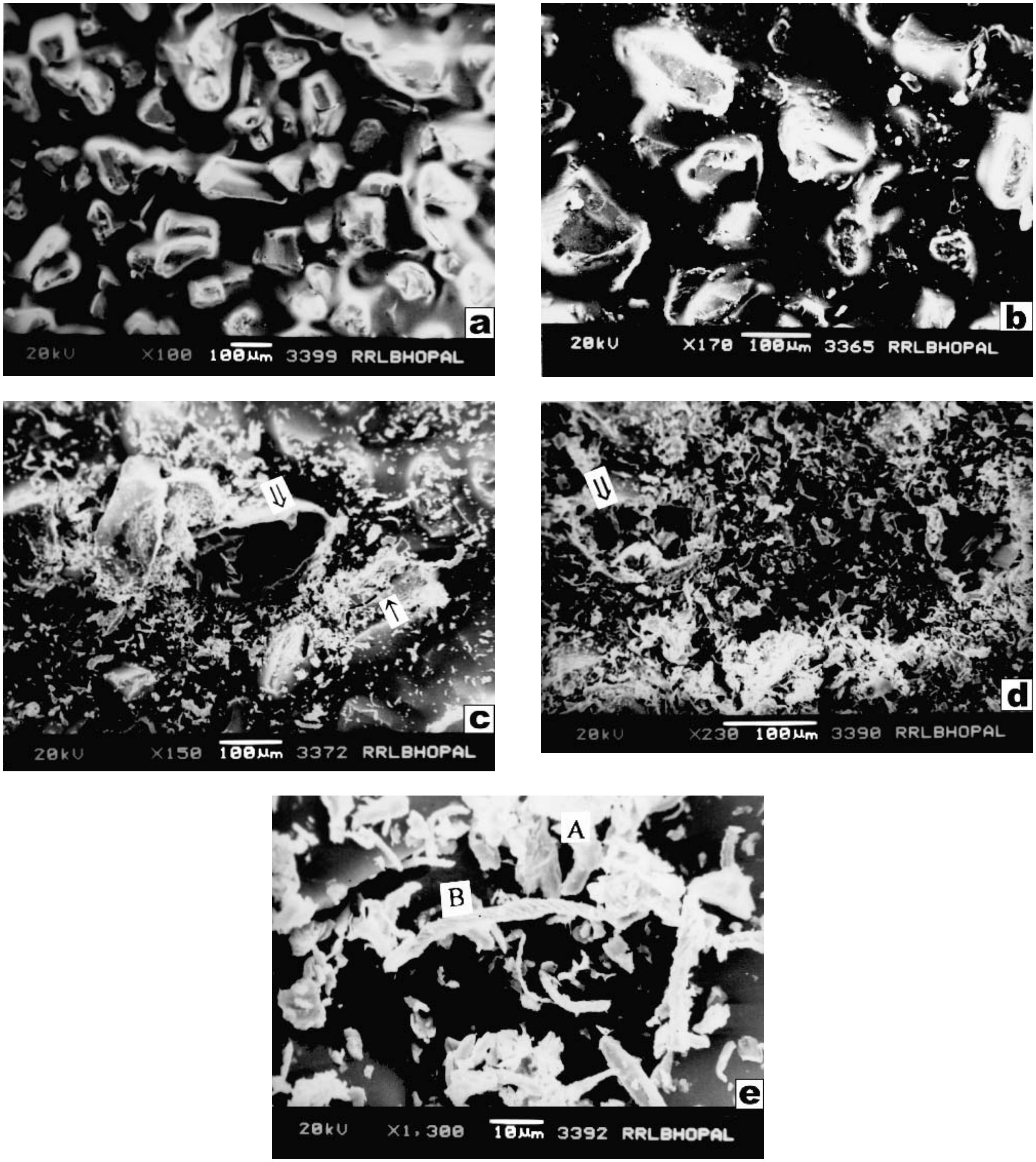

Fig. 7 Abrasive medium (a) prior to and (b-e) after abrading the specimens of (b) the layer of NCB powder with WC, (c) the layer of NCB powder without WC, and (d and e) the substrate tested over a sliding distance of 78 m at a load of 7 N using fresh abrasive. (A, flakes; B, machining chips; single arrow, fracturing/fragmentation of the abrasive; double arrow, partial removal of the abrasive)

size of the abrasive with respect to that of the specimen also influence the wear response of the latter.[12,15] The presently used abrasive comprised ~ 100 µm silicon carbide particles embedded on paper (Fig. 7a). For the softer substrate, severe wear took place (due to the large difference in the hardness of mild steel and SiC abrasive particles) through cutting, ploughing, and wedging of the surface (Fig. 5e and f). This can also be evidenced by the presence of large-size machining chips and flakes in the debris (Fig. 7d and e). Figure 2 and Fig. 3 also indicate higher wear rates for the substrate. Large transfer layers along with the subsurface cracks (Fig. 6e) are also indicative of more severe abrasion of the softer substrate than that of the deposited layers of the NCB powder with and without WC. Wear rate increased significantly with increasing load (Fig. 2) because of the larger depth of cut on the (softer substrate) matrix at higher load.[16,17] Increase in the wear rate of the layer of NCB powder containing WC with increasing load was minimum (Fig. 2) in view of the presence of (hard) tungsten carbide particles on the wear surface, which resisted the penetration of the abrasive particles into the matrix. This was also supported by the formation of shallow wear grooves (Fig. 5a and b).

Marginal reduction in the wear rate with distance for abrasion of the substrate against the fresh abrasive medium (Fig. 3) could be attributed to subsurface hardening.[18] In addition, gradual reduction in the cutting efficiency of the abrasive through shelling, capping, clogging, and attrition[12,19] with distance while the degraded abrasive was used, led to decrease in the wear rate of the samples in all cases (Fig. 3).

It may be noted that during sample preparation, final polishing is done with loose abrasive particles. If the sample comprises hard microconstituents sufficiently large in size and embedded in a relatively softer matrix, the loosely held polishing-abrasive particles freely and effectively enter into the space between the hard microconstituents. As a result, the softer matrix gets abraded to a larger extent than the harder phases, as observed in three-body (low-stress) abrasion, leading to the protrusion of the hard phases above the (softer) matrix.[20,21] This was very much the case with the samples of the layer of NCB powder containing WC particles prior to (high-stress) abrasion in this study. During high-stress abrasion, the rigidly held abrasive particles penetrate the specimen surface to the same extent in all regions of contact irrespective of the nature of various phases present therein.[16,17] In other words, the depth of cut made by the abrasive particles on the specimen surface is that of the one on the harder/stronger microconstituents present therein. Obviously, the hard phases protruding above the matrix get abraded first and the extent of their protrusion above the surface is reduced. Accordingly, roughness of the specimen surface decreased after wear testing, as observed for the layer of the NCB powder with WC (Table 2). For the remaining samples, i.e., the substrate and the layer of the powder without WC particles, the surface was smooth initially, wherein the depth of cut made by the abrasive during abrasion increased the roughness after wear testing (Table 2).

5. Conclusions

- Abrasive wear resistance of the substrate improved after depositing a layer of a nickel chromium boron NCB powder. Presence of tungsten carbide in the layer of the NCB powder further improved the wear properties.
- Wear rate increased with load. Furthermore, the extent of increase was the least for the layer of the NCB powder containing hard WC particles, followed by that of the layer of the NCB powder without WC, the substrate revealing maximum extent of increase (Fig. 2).
- Wear rate of the samples reduced marginally with sliding distance when fresh abrasive particles were used throughout the tests. However, wear rate decreased with sliding distance to a greater extent when the abrasive remained unchanged (i.e., degraded) during the test.
- Presence of flakes and machining chips in the debris suggests that wear was caused by ploughing and cutting actions of the abrasive. Changes in the subsurface regions were minimal for the layers of the NCB powder with and without WC. Accordingly, the debris formed in this case was finer than in the case of the softer substrate.

References

1. R. Dasgupta, B.K. Prasad, O.P. Modi, S. Das, A.K. Jha, and A.H. Yegneswaran: "Surface Engineering for Improving Performance of Mining and Agricultural Implements," *Surf. Eng.,* 1997, *13*, pp. 123-27.
2. G. Schmidt and S. Steinhauser: "Characterization of Wear Protective Coatings," *Tribo. Int.,* 1996, *29*, pp. 207-14.
3. B.R. Marple, B. Arsenault, and J. Voyer: in *Thermal Spray: A United Forum for Scientific and Technological Advances*, C.C. Berndt, ed., ASM International, Materials Park, OH, 1997, pp. 73-84.
4. Technical Bulletin, No. COR-021/1/8-98/6000, Ador Fontech Limited, Bangalore, India.
5. P. Crook and N. Howard: "Friction and Wear of Hardfacing Alloys," in *ASM Handbook*, Vol. 18, Peter Blau, ed., ASM International, Materials Park, OH, 1992, pp. 758-65.
6. H.C. Lee and J. Gurland: "Hardness and Deformation of Cemented Carbide," *Mater. Sci. Eng.,* 1978, *33*, pp. 125-33.
7. K. Jia and T.E. Fischer: "Abrasion Resistance of Nano Structured and Conventional Cemented Carbides," *Wear,* 1996, *200*, pp. 206-14.
8. J. Larsen-Basse: "Effect of Compositions, Microstructure and Service Conditions on the Wear of Cemented Carbide," *J. Met.,* 1983, *35,* pp. 35-42.
9. B.K. Prasad, S. Das, R. Dasgupta, O.P. Modi, A.K. Jha, and A.H. Yegneswaran: "Two-Body Abrasion Characteristics of a Zinc-Based Alloy: Effects of SiC Particle Reinforcement and Related Factors," *J. Mater. Sci. Lett.,* 1998, *17*, pp. 901-3.
10. D.P. Mondal, S. Das, A.K. Jha, and A.H. Yegneswaran: "Abrasive Wear of Al Alloy-Al_2O_3 Particle Composite: A Study on the Combined Effect of Load and Size of Abrasive," *Wear,* 1998, *223*, pp. 131-38.
11. A.T. Alpas and J.D. Embury: "Sliding and Abrasive Wear Behaviour of an Aluminum (2014)-SiC Particle Reinforced Composite," *Scr. Metall.,* 1990, *24*, pp. 931-33.
12. T. Hisakado, H. Suda, and T. Trukui: "Effects of Dislodgment and Size of Abrasive Grain on Abrasive Wear," *Wear,* 1992, *155*, pp. 297-307.
13. A. Wang and H.J. Rack: "Abrasive Wear of Silicon Carbide Particulate and Whisker Reinforced 7091 Aluminum Matrix Composites," *Wear,* 1991, *146*, pp. 337-48.
14. A. Banerjee, S.V. Prasad, M.K. Surappa, and P.K. Rohatgi: "Abrasive Wear of Al-Alloy-Zircon Particle Composite," *Wear,* 1982, *82*, pp. 141-51.
15. M. Singh, A.K. Jha, R. Dasgupta, O.P. Modi, and B.K. Prasad: "Effect of Abrasive Size on the Wear Behaviour and Al-Alloy Sillimanite Particle Composite," *Proceedings of the Third International Conference on Advanced Composites,* E.S. Dwarkadasa and C.G. Krishnadas Nair, ed., FAME, Bangalore, 2000, pp. 625-31.
16. B.K. Prasad, A.K. Jha, O.P. Modi, S. Das, and A.H. Yegneswaran: "Abrasive Wear Characteristics of Zn-37.2 Al-2.5 Cu-0.2 Mg Alloy Dispersed with Silicon Carbide Particles," *Mater. Trans. JIM,* 1995, *36*, pp. 1048-57.
17. B.K. Prasad, S. Das, A.K. Jha, O.P. Modi, R. Dasgupta, and A.H.

Yegneswaran: "Factors Controlling the Abrasive Wear Response of a Zinc-Based Alloy Silicon Carbide Particle Composite," *Composites,* 1997, *28A*, pp. 301-8.

18. O.P. Modi, B.K. Prasad, S. Das, A.K. Jha, and A.H. Yegneswaran: "Abrasive Wear Behaviour of an AISI 5132 Steel Under Low Stresses," *Mater. Trans. JIM,* 1994, *35*, pp. 67-73.
19. A.P. Mercer and I.M. Hutchings: "The Deterioration of Bonded Abrasive Papers During the Wear of Metals," *Wear,* 1989, *132*, pp. 77-97.
20. B.K. Prasad, S.V. Prasad, and A.A. Das: "Abrasion-Induced Microstructural Changes and Material Removal Mechanisms in Squeeze Cast Aluminum Alloy-Silicon Carbide Composites," *J. Mater. Sci.,* 1992, *27*, pp. 4489-94.
21. B.K. Prasad, S.V. Prasad, and A.A. Das: "Mechanisms of Material Removal and Subsurface Work Hardening During Low-Stress Abrasion of a Squeeze-Cast Aluminum Alloy-Alumina Fibre Composite," *Mater. Sci. Eng. A,* 1992, *156A*, pp. 205-9.