HVOF sprayed Inconel 718/cubic boron nitride composite coatings: microstructure, microhardness and slurry erosive behaviour

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Abstract
In the present work Inconel 718 based composite coating with varying cBN were developed on SS304 substrate using high-velocity oxy-fuel (HVOF) technique. The developed coatings were subjected to microstructural, x-ray diffraction, microhardness and adhesion strength studies. The uncoated and composite coatings were subjected to slurry erosion test with varying slurry concentration (10%–40%), slurry rotational speed (300–1500 rpm) and test duration (5–25 h). Cross-sectional analysis of composite coating suggested formation of lamellar structure with good splat/splat bonding as well as with the substrate material. Both microhardness and slurry erosion resistance of Inconel 718/20% cBN coating was found to be significantly higher than that of uncoated and other composite coatings. For all slurry erosion test conditions the composite coatings were found to be superior to that of uncoated substrate. Overall composite coatings showed failure mechanism starting from plastic deformation to spalling while uncoated substrate showed deep crater with heavy ploughing.

1. Introduction
In hydropower, mining and marine industries the principal component or equipment such as turbines, flotation cells, pipelines, propellers and valves are often subjected to degradation. The degradation is caused by repetitive impact of solid particles suspended in liquid during slurry transportation. These solid particles are often found to have irregular and angular shapes with rough surface enough to cause erosion or abrasion. Due to slurry related degradation the equipment’s are prone to frequent maintenance which only affects the performance but also decrease the design life span. However transportation of slurry containing particulates not only involves erosion but it can involve abrasion and corrosion as well. The extent of wear is so intense in pump propellers that the wear depth can run into several millimeters in within hours of service period. Keeping the detrimental consequences of slurry erosion in view many research laboratories across the world are studying how to increase the life span and reduce maintenance cost. In this regard there is a dire need of surface engineering which uses coatings and treatments to counter the degradation of surface of components [1–4].

Surface engineering enhances the properties of component surface to impart protection against corrosion, wear and high temperatures. Thermal spray coating is one of the surface engineering techniques to enhance surface properties by depositing wide range of materials on different types of substrates. High-velocity oxy-fuel technique (HVOF) belongs to thermal spraying which is capable of depositing coatings with lower porosity content and high bond strength [5–8]. Verdian et al.[9] conducted comparative study on the corrosion behavior of NiTi intermetallic coatings produced by high-velocity oxy-fuel and atmospheric plasma spray (APS) techniques. Both the coatings had low porosity but APS coatings showed number of microcracks in the microstructure. The Tafel polarization results revealed better passive ability and corrosion performance for
HVOF coatings as compared to APS coatings. Mohammadi et al [10] reported hot corrosion performance of low vacuum plasma spray and HVOF sprayed CoNiCrAlYSi coatings. The HVOF sprayed coatings showed better hot corrosion resistance due to nucleation of stable $\alpha$-Al$_2$O$_3$ protective layer while the same was prone to easy spallation. These studies indicated that HVOF technique was quite better than other coating techniques in terms of deposition of coatings.

Several coating materials have been deposited on the surface various substrates using HVOF technique to enhance the resistance against slurry erosion related failure. Peat et al [11] evaluated the performance of HVOF sprayed WC-Co-Cr, Al$_2$O$_3$ and Cr$_3$C$_2$-NiCr coatings subjected to slurry erosion with silica sand of average particle size of 0.355 mm as solid media. Compared to all coatings, the uncoated S355 steel substrate suffered highest mass ($\sim$122 mg) and volume loss ($\sim$124 mm$^3$). Singh et al [12] studied the slurry erosion response of uncoated and WC-Co-Cr $+$ Ni-Gr-B-Si coated CA6NM (13Cr4Ni) steel. Erosion rate of uncoated steel was found to be very high than HVOF coated steel in all varying conditions of slurry concentration, impact angle and particle size. The dominant erosion mechanism for uncoated steel at normal and 30$^\circ$ impact angle was formation of craters and microcutting mechanisms respectively. Ramesh et al [13] reported the slurry erosion and corrosion behavior of titania coated mild steel substrate. TiO$_2$ coated mild steel substrates ($\sim$16 mg) showed significant resistance to slurry erosive wear loss when compared to that of uncoated substrate ($\sim$40 mg). However with the increase in impinging particle size and slurry rotation speed the weight loss increased. These works showed that the HVOF sprayed coatings were successful in providing slurry erosion significant resistance to the substrate surface.

Very minimal amount of work is carried out on development of Inconel 718/cBN composite coatings using HVOF and studying its slurry erosion behavior. Owing to its high hardness, cBN was suggested as reinforcing material for Inconel 718 for obtaining better slurry erosion resistance. Although few works on Inconel based composite coatings like Inconel 718/YSZ/Gd$_2$Zr$_2$O$_7$ have been studied but their objective was to explore high temperature oxidation behavior. They found that the Inconel 718/YSZ/Gd$_2$Zr$_2$O$_7$ was found to have better oxidation resistance than that of pure Inconel 718. This paper reports the development of Inconel 718/cBN composite coatings using HVOF technique. The investigation is based upon the outstanding properties offered by Inconel 718 alloy and cubic boron nitride (cBN). The studies concerning with these materials individually are very less and rarely used in combination [14–17]. The slurry erosive behavior of Inconel 718/cBN composite coatings was studied at different sand particle concentration, slurry rotational speed, time durations and particle size.

2. Experimentation

2.1. Materials and methods

In this study starting powders to make composite coating were cBN (Make: Hefei EV Nano Technology Company Ltd, China, 20–45 $\mu$m) and Inconel 718 (Make: Huarui Group Ltd, China, $\sim$30 $\mu$m). Figures 1(a) and (b) shows the SEM images of as received cBN and Inconel 718 particles having irregular and spherical morphology respectively. X-ray diffraction (XRD) patterns of these powder particles are shown in figure 2 (Make: PANalytical X’pert3). The composite coating powder were prepared by varying the cBN content from 5–20 wt% in the steps of 5 wt% using planetary ball milling. The ball milling was carried out for a short duration of 30 min to blend both the starting powders. SEM images of the ball milled Inconel718/15%cBN powder are shown in figures 1(c) and (d). The particle size of composite powders was measured using particle size analyzer (Make: Mastersizer 2000 & Malvern) and was found to be in the range of 15–45 $\mu$m. Substrate material chosen for this study was SS 304 stainless steel which is widely used in food processing equipment, heat exchangers and chemical containers. The substrate to be coated was cut in to $75 \times 25 \times 8$ mm$^3$ dimensions and cleaned with acetone to remove dust or grease from the surface. The cleaned substrate was subjected to grit blasting using alumina particles of average particle size of 80 $\mu$m as abrasive media. The grit blasting is done to enhance the bonding between the substrate and composite coating. HVOF technique was used to deposit the composite coating with varying amount of cBN using Hipojet-2700-M HVOF powder spray system at PES institute of Technology, Bangalore. Spraying parameters employed for coating deposition are given in table 1. In order to obtain coating thickness in the range of 300–400 $\mu$m, the spraying cycles was repeated up to 16 times. Photograph of as received, polished and coated SS 304 stainless steel substrate is shown in figures 3(a) to (c). The color of substrate was found to change from dark greenish for polished and greyish for coated substrate materials.

2.2. Testing and characterization

Surface roughness of base material, grit blasted substrate (SS304), after Inconel 718/15%cBN composite coating deposition and after slurry erosion test was measured using MARSURF XR 1 Roughness Measuring Station.
Surface roughness of base material and grit blasted substrate (SS304) was found to be 0.08 and 6.53 μm respectively and is presented in figure 4. In order to study the microstructure of deposited coatings, standard metallographic procedures were followed. Initial polishing was carried out using emery papers followed cloth polishing using 0.5 μm diamond paste. Cross sectional after deposition and surface
morphology after slurry erosion studies was analyzed using scanning electron microscope (Make: Tescan Vega3). Microhardness measurements were carried out as per ASTM E 384 standards on both substrate and composite coatings. A load of 100 g for a dwell period of 10 s was conducted and about 10 indentations were and average of those is given here. Porosity and adhesion strength tests were conducted as per ASTM E 2109-01 (Method A) and ASTM C 633-79 standards respectively. Adhesion strength of composite coatings was

| Parameters                      | Values set  |
|---------------------------------|-------------|
| LPG (propylene) flow            | 60 LPM      |
| Oxygen flow                     | 250 LPM     |
| Air flow                        | 650 LPM     |
| Nitrogen (carrier gas)          | 6 kg cm⁻²   |
| Powder feed rate                | 60 g min⁻¹  |
| Standoff distance               | 400 mm      |
| Feed stock size                 | 15–45 μm    |

Figure 3. Photographs of the substrate in (a) as received, (b) polished and (c) coated conditions.

Figure 4. Surface roughness of (a) base material (SS304) and (b) grit blasted substrate (SS304).
determined on cylindrical samples of 25 mm diameter as per standard tensile adhesion test. Slurry erosion test was conducted on uncoated and composite coated substrates using slurry pot erosion tester (Make: Ducom Instruments, India). The test was conducted in pot containing slurry of silica sand, 3.5%NaCl and distilled water. Each sample of $75 \times 25 \times 8$ mm$^3$ dimensions were cut using laboratory high precision diamond cutting machine and were fixed in the spindles provided in the slurry pot. Effect of varying silica sand concentration (10–40 wt%), slurry rotational speed (500–1500 rpm) and time durations (5–25 h) was studied. The initial and final weight of all the samples was taken to analyze the weight loss which is expressed in mg. The weight of the specimens was measured by using Electronic balance, Make: Shimdzu Corporation, Capacity: 220 g and Readability: 0.1 mg.

3. Results and discussion

3.1. Microstructural analysis of coatings

Figure 5 shows the SEM micrographs of Inconel 718/15%cBN composite coating deposited on the surface of SS304 stainless steel. Cross sectional image as shown in figure 5(a) suggests the formation of lamellar structure with good splat/splat bonding as well as with the substrate material. The lamellar structure is a result of complete melting of composite powder particles during spraying and high velocity impact to the substrate surface. Due to high temperatures involved the fully melted particles are deposited on the substrate surface with high impact velocities. Each droplet will form a thin layer of lamella which keeps on building at rapid pace to form a lamellar structured coating. To obtain good dense coating it is necessary to have sufficient plastic deformation and tight stacking with other deposited splats. In case of HVOF coating process the composite powders are propelled at high impact velocities at the substrate. Due to high temperature the particles are either melted completely or partially which is sufficient enough to cause bonding with other splats and the layers of splats are tightly packed with one another. In addition to impact velocity and temperature, the optimal stand-off distance helped in achieving better cohesive strength within the composite coating. Further the composite coatings had relatively less amount of porosity which is again attributed to the high impact velocities and optimal stand-off distance. From the micrograph it was observed that the composite coating was deposited with nearly uniform thickness of $\sim 372$ $\mu$m. The cBN particles are found to be fairly dispersed in the Inconel 718 matrix with some amount clustering at several regions. In figure 5(b), the surface morphology of Inconel 718/15%cBN composite coating shows surface with very high roughness. The formation of rough surface can be due to surface roughness of the substrate or nature of the spray coating [18]. In this case the formation of such surface can be attributed to nature of coating it contains extremely hard (Knoop hardness $\sim 4700$ kgf mm$^{-2}$) and high melting point ($\sim 3027^\circ$C) cBN particles. When the composite powder with high weight percentage of cBN particles are sprayed than there are high chances that they might not undergo complete melting. These partially melted cBN particles along with Inconel 718 particles do contribute do the increase in surface roughness of the coating. This can be confirmed by figure 5(a) which shows the presence of un-melted cBN particles at the splat boundaries. Further due to deposition of partial melted and un-melted powder particles, open pores were observed in many regions. X-ray diffraction pattern of the Inconel 718/15%cBN composite coating is shown in figure 6. From pattern it can be

![Figure 5. SEM micrographs of (a) cross section and (b) surface morphology of Inconel 718/15%cBN composite coating.](image-url)
observed that both the constituents of composite coating are present with well defined peaks (cBN = 44.30°, 50.79°, 74.57°; Inconel 718 = 72.48°, 88.15°). No additional peaks pertaining to any reaction or formation of oxide inclusions were observed. This is attributed to the chemical inertness and phase stability of cBN particles which is retained even at elevated temperatures. The composite particles travelling at high velocity are subjected to minimal in-flight exposure time due to this the particles are less prone to oxidation. This why no considerable amount of oxides were formed otherwise would have been detected in XRD [19].

### 3.2. Microhardness

The porosity percentage, microhardness and adhesion strength of substrate and composite coatings is presented in Table 2. It can be observed that the porosity of coatings tend to increase with the increase in cBN content. Lowest porosity content is observed for coating containing comprising of Inconel 718 with no addition of cBN particles. Highest porosity content of 1.68 ± 0.40% was obtained for Inconel 718/20%cBN composite coating. The increase in porosity percentage can be attributed to formation of open pores in between partial melted and un-melted powder particles. The microhardness of the composite coating largely depends on the arrangement of splats and the dispersion of cBN particles in the Inconel 718 matrix. Table 2 shows the microhardness of uncoated and coated SS304 substrate with varying cBN content. As observed from the table, the microhardness of composite coatings increased with the increase in cBN content from 5% to 20%. Compared to the microhardness of uncoated SS304 steel which was 312.42 HV, the composite coating with lowest and highest cBN content (5 and 20%) had significantly higher values of 485.38 and 525 HV respectively. From results it is clearly understood that the composite coating microhardness is strongly affected by presence of cBN particles. In this study the significant increase in microhardness of composite coating can be attributed to multiple strengthening mechanisms which include dispersion strengthening induced by cBN particles, grain refinement and work hardening. This is mainly because the microhardness of Inconel 718 coating without any cBN particles

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**Table 2.** Porosity, microhardness and adhesion strength of substrate and composite coatings.

|                 | Porosity, % | Microhardness (HV) | Adhesion strength (MPa) |
|-----------------|-------------|---------------------|-------------------------|
| Uncoated SS304  | —           | 312.42              | —                       |
| 0%cBN           | 0.98 ± 0.22 | 476.16              | 68                      |
| 5%cBN           | 1.05 ± 0.16 | 485.38              | 71                      |
| 10%cBN          | 1.21 ± 0.45 | 518.12              | 75                      |
| 15%cBN          | 1.45 ± 0.68 | 512.22              | 83                      |
| 20%cBN          | 1.68 ± 0.40 | 525                 | 81                      |

![Figure 6. X-ray diffraction pattern of Inconel 718/15%cBN composite coating.](image)
was found to be 476.16 HV while after addition cBN particles it started increasing. With the increase in cBN content the microhardness of composite coatings increased in comparison with that of uncoated substrate. The dispersion of cBN particles is fairly uniform in the Inconel 718 matrix with good bonding which is very important from mechanical properties point of view. Otherwise poor adhesion of reinforcement particle with the matrix can lead to poor hardness of resulting composite coating [20]. The uniformly dispersed hard cBN particles hinder the grain growth or grain boundary sliding thereby causing enhancement in microhardness.

Further the grain size will decrease with increase in cBN particles content and according to Hall-Petch relationship the hardness will increase as the grain decreases. Finally, high velocity impact of cBN particles causes considerable amount of work hardening on Inconel 718 matrix during deposition process. The shorter stand-off distance ensures high impact velocities due to which cBN particles causes enough work hardening. The increase in cBN particle content further enhances the work hardening rate resulting in increase in microhardness. These findings are in line with that reported by Luo et al [16] where addition of cBN particles to NiCrAl matrix enhanced the microhardness by virtue of dispersion and work hardening. Adhesion strength of coatings was also performed and the obtained values are presented in table 2. It can be observed that the adhesion strength tends to increase with increase in cBN particle content in the coatings until it reached 15%. After 15% of cBN particle content the adhesion strength of composite coating tends to decrease marginally. Generally the adhesion strength largely depends upon interaction between coating being deposited with substrate and between the individual splats. Voids or cracks near substrate/coating interface or between individual splats can result in poor adhesion strength of coatings. In present work the highest adhesion strength of 70 MPa was obtained for Inconel 718/5% cBN composite coating and lowest value of 54 MPa was obtained for Inconel 718/20% cBN composite coating. With marginal increase in porosity content, the adhesion strength composite coating is found to be decreasing. The presence of pores at the vicinity of splat/splat interface can initiate stress in the coating which in turn dilutes the adhesion strength of the coatings [22, 23]. However the drop in adhesion strength is not so significant for Inconel 718 composite coating with 5% and 10% as compared to Inconel 718 coating without cBN particle content. This can be attributed to the good bonding between Inconel 718 splats with cBN particles.

### 3.3. Slurry erosion behavior

Effect of various parameters like slurry concentration, slurry rotational speed and test duration on slurry erosion behavior of uncoated and Inconel 718/cBN composite coated SS304 substrate is studied and discussed in upcoming sections. Here for all cases the impinging particle size was kept constant to 300 μm well rest of the test parameters were varied.

#### 3.3.1. Effect of slurry concentration

Figures 7(a)−(d) show the effect of varying slurry concentration (10%−40%) on weight loss of uncoated and Inconel 718/cBN composite coated SS304 substrates. Here the slurry rotation speed and time duration were kept constant for 500 rpm and 5 h. As shown in figure 7(a), for 10% slurry concentration the weight loss was found to decrease with the increase in cBN content. Highest weight loss of 14.3 g was displayed by uncoated substrate while lowest value of 1.1 g was displayed by Inconel 718/20% cBN composite coating. The same trend was displayed by 20, 30 and 40% slurry concentration test results where the uncoated substrate showed lowest erosion resistance while composite coating with 20% cBN particles displayed highest erosion resistance. All composite coatings displayed the increase in erosion resistance with the increase in cBN particle content. With respect to increase in slurry concentration the erosion resistance was found to decrease. The erosion resistance is decided based upon the weight losses of uncoated substrate and Inconel 718/20% cBN composite coating only.

The reason behind choosing Inconel 718/20% cBN composite coating is because this composite coating showed least weight loss when compared to rest of the composite coatings. The erosion resistance of Inconel 718/20% cBN composite coating was about 92.30% higher than that of uncoated substrate. However as shown in figures 7(b)−(d), it is observed that with the increase in slurry concentration to 20, 30 and 40%, the erosion resistance of Inconel 718/20% cBN composite coating decreased to 82.40%, 78.43% and 80.43%. However slight increase in erosion resistance was shown by 40% slurry concentration when compared to 30%. Further it is interesting to note that the weight loss for all samples tend to decrease with the increase in slurry concentration. With the increase in slurry concentration the number of impinging particles is increased due to which the probability of reaching the target surface for becomes smaller. This is attributed to multiple collisions of impinging particles among themselves making them to lose their way from reaching the target. In addition to this the shielding effect provided by the rebounding particles also minimizes the number of impinging particles reaching the target surface. These rebounding particles not only restrict but also retard the velocity of fresh incoming particle thereby reducing the interaction of impinging particles with target surface. Due to these reasons the weight loss of all samples was found to decrease significantly. Similar observations were reported by
Goyal et al [24] where due to high slurry concentration only fraction of abrasive particles where hitting the target surface while rest of them lost their path due to mutual collisions.

3.3.2. Effect of slurry rotational speed

Figures 8(a)–(c) shows the weight loss of uncoated and Inconel 718/cBN composite coated SS304 substrates as a function of varying weight percentage of cBN particles for different slurry rotational speeds. Since the slurry rotational speed is varied, the rest of parameters such as slurry concentration and test duration were kept constant for 20% and 5 h. It is observed from figure 8(a) that for 500 rpm the highest weight loss observed for uncoated SS304 substrate while lowest weight loss was observed for Inconel 718/20%cBN composite coating. For this speed the resistance offered by Inconel 718/20%cBN composite is 82.40% higher than that of uncoated substrate. Even in case of 1000 and 1500 rpm rotational speeds the highest slurry erosion resistance was displayed by Inconel 718/20%cBN composite coating while the uncoated substrate displayed low slurry erosion resistance (see figures 8(b) and (c)). For rotational speed of 1500 rpm the Inconel 718/20%cBN composite coating displayed 69.41% higher resistance than that of uncoated substrate. From these observations it is clear that with the increase in slurry rotational speed the erosion resistance of Inconel 718/20%cBN composite coating is decreased from 82.40% for 500 rpm to 69.41% for 1500 rpm. It is well known that erosive wear occurs due to relative motion between surface and impinging particle. So if the rotational speed is increased the velocity of impinging particles will also be increased resulting in enhanced erosion rate. However increase in weight loss with the increase in rotational speed is not so significant indicating better erosion resistance imparted by the composite coating to the SS304 substrate. Further if weight loss of individual samples is considered then it is observed that uncoated substrate and coated substrates showed highest weight loss for rotational speed of 1000 rpm. This might due to shielding effect by rebounding particles which tend to restrict the incoming fresh impinging particle from reaching the target surface [25]. With the increase in slurry rotational speed from 500 to
100 rpm the weight loss of all samples was found to increase but thereafter decrease in weight loss was noticed. With the increase in rotational speed the kinetic energy of impinging particles will increase due to which they will be more efficient in material removal. In case of high rotational speed (1500 rpm) the particles rebound at very high velocity due to which they tend to retard the velocity or restrict the incoming fresh impinging particle from reaching the target surface. Whereas in case of 1000 rpm samples the rebounding particle might not have effective interaction with that of fresh incoming particle due to which the weight loss is higher when compared to that of 500 or 1500 rpm samples.

3.3.3. Effect of test duration

The weight loss of uncoated and Inconel 718/cBN composite coated SS304 substrates as a function of varying weight percentage of cBN particles and test durations are shown in figures 9(a)–(e). The test duration was varied from 5 to 25 h while sand concentration and rotational speed were kept constant to 20% and 500 rpm. As shown in figure 9(a), the samples subjected to 5 h test duration showed a trend of decrease in weight loss of composite coatings with the increase in cBN particle content from 5 to 20%. The uncoated substrate showed highest weight loss of 10.8 g while the composite coating with 20% cBN content showed lowest weight loss of 1.9 g. One can observe that the weight loss of uncoated substrate was about 82.40% higher than that of Inconel 718/20%cBN composite coating. On the other hand for test duration of 25 h, the uncoated substrate showed 83.13% higher weight loss than that of Inconel 718/20%cBN composite coating. Similar results were observed for rest of the test durations where uncoated showed highest weight loss while Inconel 718/20%cBN composite coating showed minimal weight loss. The addition of cBN particles had positive effect on the erosion resistance of Inconel 718 matrix with respect to test duration. It can be seen that the increase in test duration didn’t have significant impact on the weight loss as both 5 and 25 h test duration showed similar weight loss differences.

Figure 8. Effect of slurry rotation speed on weight loss of uncoated and Inconel 718/cBN composites coatings.
Only in case of test duration of 10 h the weight loss was highest where the uncoated substrate showed 86.95% higher weight loss than that of Inconel 718/20%cBN composite coating. The increase in weight loss at this test duration can be attributed to continuous impinging action of sand particles on the target surface. It can be presumed that the irrespective of test duration the composite coatings showed similar slurry erosion wear resistance for all test duration and maintained the similar weight loss differences between the uncoated and coated substrates [26]. This is attributed to presence of hard cBN particles embedded in Inconel 718 matrix with

Figure 9. Effect of test duration on weight loss of uncoated and Inconel 718/cBN composites coatings.
good interfacial bonding and despite of increase in test duration they still were capable of providing excellent erosion resistance. Overall it is observed that increase in slurry concentration and test duration the weight loss is decreased. Exception was slurry rotational speed where weight loss increased with increase in rotational speed. However if individual are considered than it was the uncoated substrates which suffered from highest weight loss and Inconel 718/20% cBN composite coating the lowest. Significant control in weight loss was attributed to high hardness and high content of cBN particles in the Inconel 718/20% cBN composite coating.

3.4. Eroded surface analysis

The mechanisms responsible for material removal under different slurry erosion test conditions were analyzed using SEM. Figures 10(a)–(f) shows the SEM of eroded surface of uncoated and Inconel 718/cBN composite coatings under varying slurry concentration (10% and 40%). From figure 10(a) it is observed that at low slurry concentration of 10% the uncoated substrate showed erosion was mainly due to ploughing and formation of craters. The yellow dotted lines and circles clearly indicate the formation of craters and ploughing in the SEM micrograph. Some of the ploughing marks are found to have dug deep into the substrate surface causing significant material loss. Along with this the presence of craters at several places does indicate that it is one of main contributor for weight loss. The formation of crater can be attributed to repeat impinging of particles on the surface with an angle close to 90°. On the other hand the substrate whose test was conducted for 40% slurry concentration showed large amount of plastic deformation followed by few micro-cutting marks (see figure 10(b)). Unlike previous case the extent of micro-cutting was minimal since most of the surface was covered with plastic deformation. It is well known that the erosion or weight loss of coatings starts with plastic deformation followed by micro-cutting. In this case the presence of large plastic deformation regions suggests that the micro-cutting process is yet to begin. This is why the weight loss for this sample at high slurry concentration (40%) is found to be lower than that of low slurry concentration (10%). In case of composite coatings as shown in figures 10(c) and (e) the test conducted at 10% slurry concentration showed that the eroded surface was composed of spalling and micro-cracks at many regions. However in case of Inconel 718/20% cBN composite coating the extent of spalling was minimal as compared to that of composite coating with 5% cBN. However both the surfaces showed significant amount of spalling when compared to those tested at 40% slurry concentration (see figures 10(e) and (f)). In case of latter the extent spalling is comparative less because of mutual collisions and rebounding of impinging particles which reduce the efficiency to reach the target surface. With the increase in slurry concentration the numbers of impinging particles per unit volume increases but during striking the target surface they tend lose their path due to the mutual collisions and reduction in velocity of impinging particles due to rebounding impact of previous impinging particles. Due to this the number of particles trying to reach the target surface is quite less when compared to those in low slurry concentration. This is the reason why the weight loss of composite coatings is considerably lower for high slurry concentration and higher for low slurry concentration.

The eroded surfaces of composite coatings with 5 and 20% cBN particles for slurry rotational speed of 500 and 1500 rpm are shown in figures 11(a)–(d). For slurry rotational speed of 500 rpm, the eroded surfaces of both the composite coatings were composed of plastic deformation, micro-cracks and spallation. Figure 10(a) shows that at low cBN content (5%) the composite coating showed formation of micro-cracks and spallation as major erosion mechanisms. Due to continuous impinging of abrasive particles the micro-cracks are formed in the coatings which tend to propagate in the weak regions such as pores or interface between un-melted and completely melted powder particles. When such micro-cracks are intersected at both surface and sub-surface level the removal of splats takes place. In case of higher cBN content (10%) the composite coating showed features corresponding to that of plastic deformation and few micro-cracks. Due repeated striking of abrasive particles the surface undergoes large plastic deformation but due to presence of high cBN particles content which are projected in due to course of time take much of the impacts leading to minimal weight loss. This is why the spalling of coating due to impact of abrasive particles is quite minimal in case of Inconel 718/20% cBN composite coating since (see figure 11(b)). However with the increase in rotational speed to 1500 rpm the extent of micro-crack formation and spallation increases to very significant level especially for Inconel 718/20% cBN composite coating. Generally it is expected that the increase in rotational speed increases the erosion rate as the size and length of the micro-cracks increase causing spallation of large sized splats [28, 29]. Due to weak interfaces between un-melted and completely melted splats and increased rotational speed ensures increase in local stresses which leads to formation of micro-cracks in the Inconel 718/5% cBN composite coating (see figure 11(c)). These micro-cracks propagate along the weak regions and result in removal of splats very easily. Compared to 500 rpm rotational speed, the effect of impact velocities will be very high in 1500 rpm which is why the formation of micro-cracks and removal of splats is quite intense. But compared to 5% cBN composite coating the extent of spallation is comparatively less in case of 20% cBN composite coating which is attributed to its high hardness. In case of Inconel 718/20% cBN composite coating formation of micro-cracks is limited due
to high hardness of the coatings and presence of large number of cBN particles which are very hard to dislodge due to good interfacial bonding and tends to protect the matrix material from erosion [30].

Figures 12(a)–(d) shows the SEM micrographs of eroded surface of Inconel 718 composite coatings with 5% and 20% cBN particles taken after 5 and 25 h test durations. Figure 12(a) shows the eroded surface of Inconel 718/5%cBN composite coating obtained for test duration of 5 h. The eroded surface was composed of fragments of un-melted particles along with craters at few regions. Formation of craters is attributed to removal of un-melted splats due to repeated impact by the abrasive particles at an impinging angle close to 90°. Fragments of these un-melted particles are also seen on the eroded surface indicating that most of abrasive particles have stroke at angle close to 90°. Further in case of Inconel 718/20%cBN composite coating the eroded
surface as shown in figure 12(b) showed micro-cracks and fragments of un-melted particles. Unlike other composite coating, hardly any craters of considerable depth were found indicating resistance offered by cBN particles. The presence of micro-cracks suggests that the coating has undergone intense plastic deformation due to which the interface between un-melted and completely melted particles suffered from formation micro-cracks. The weak interface acts as stress concentration point due which the stresses start increasing leading to nucleation of micro-cracks. However shallow craters were on the surface indicating low degree of erosion in case of Inconel 718/20%cBN composite coating due to its high hardness and erosion resistance offered by cBN particles. With the increase in test duration to 25 h the eroded surface of both the composite coatings appears to be quite smoother when compared to those tested at 5 h as shown in figures 12(c)–(d). Initially the samples undergo erosion but as the test duration increases the protuberances present on the surface of coating are removed. The repeated impact of abrasive particles results in knocking of protuberances leading to smoother surface for 25 h test duration. Missing of deep craters or pits for Inconel 718/20%cBN composite coating at higher test duration is attributed to its high hardness and higher content of cBN particles. Further repeated impact striking of abrasive particles has led to material removal in the forms of fragments of coating along with spalling at few regions. It can be seen from eroded surfaces obtained for both the test durations that if the test duration is continued for longer time than the micro-cracks formed results into spalling of coating but only in few regions. Overall one can see that the uncoated substrates suffered from ploughing and formation of deep craters while in case of composite coatings the erosion mechanism initiated with plastic deformation and ended with spalling.

Figure 11. Eroded surface obtained after slurry test conducted for slurry rotational speed of (a), (b) 500 and (c), (d) 1500 rpm.
4. Conclusions

The following conclusions were drawn from the present work,

- Inconel 718/cBN composite coatings with varying cBN content (5%–20%) were successfully developed on SS304 substrate using high-velocity oxy-fuel technique with minimal porosity.

- Microhardness of composite coatings was found to significantly higher than that of SS304 substrate. Highest microhardness of 525 HV was recorded for Inconel 718/20%cBN composite coating. Enhanced microhardness is attributed to dispersion hardening and grain refinement by addition of cBN particles in Inconel 718 matrix.

- Slurry erosion test conducted showed that increase in slurry concentration and test duration didn’t had much effect of weight loss while increase in slurry rotational speed resulted in increase in weight loss.

- Out of all, uncoated SS304 showed highest weight loss for cases of slurry concentration, slurry rotational speed and test duration while Inconel 718/20%cBN composite coating showed minimal weight loss for cases.

- Eroded surface analysis showed that material removal started with intense plastic deformation followed by micro-crack, and spalling of composite coatings. Especially the Inconel 718/20%cBN composite coating showed minimal spalling as compared to uncoated substrate and other composite coatings.
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