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Solid particle erosion of HVOF sprayed (35WC-Co/NiCrBSi) coating at higher temperature

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High temperature erosion is generally encountered in boiler components in thermal power plants, especially in superheater, reheater, and economisers parts, where in fly ash particles attack the boiler components and cause high temperature erosion phenomena. It is known as fly ash erosion. The erosion behavior at elevated temperature is much different from that of room temperature erosion as there would be a higher erosion loss encountered at higher temperature due to higher plastic deformation as well as weak bonding between grains/particles. It is therefore imperative to study in depth the erosion wear assessment both at room temperature as well as at elevated temperature in the laboratory. This paper investigates thermal sprayed coatings produced by the high velocity oxygen fuel (HVOF) to improve the material performance under such conditions. 35 WC-NiCrBSi HVOF sprayed coatings were tested under high temperature (up to 700 ^oC) erosion by means of an apparatus that simulated real conditions. The results showed that under these tests conditions the 35WC-NiCrBSi coating worn about 1.4 times less than bare SS-310 steel at room temperature and 300^o C Temperature, while at 700^o C35WC-NiCrBSi worns about 2 times higher than bare SS-310 steel at 90^o impact angle. This shows 35WC-NiCrBSi erosion sensitivity at higher temperature.

Keywords: *Thermal spray coating, HVOF , high temperature erosion, impingement angles, Surface analysis.*

1.0 INTRODUCTION

Erosion is a major challenge in many engineering approach, Power plants are one of the vital major industries suffering from severe corrosion and erosion problems ensuing in the substancial lossess, the burning of coal in power plant generates a huge amount of fly ash, which motives excessive and localized erosive wear of power plant apparatus's. Erosion outcome from impact of particulates, such as coal ash, dolomite and unburned carbon particles on the surface of heated boiler tubes. It is normal believed that essentially the most erosive species within the fly ash are quartz, which is a crystalline type of SiO_2 and mullite. More than one quarter of all the boiler tube fails worldwide are brought on by fly ash erosion [1, 2] for illustration, the erosive put on is the major cause of disasters in economizer boiler tubes. The study of the mechanism of erosion is therefore tremendously important in an effort to develop suitable options to slash or even eliminate renovation systems of such equipment's.

The erosion wear mechanisms involve the removal of material from a given surface because of the impact of strong particles. The character and the magnitude of the forces during the

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contact between the surface and the particles are very most important parameters and need to be then cautiously evaluated. These forces switch energy from the particle to the target material and assess the extent and morphology of the impact deformation.

Many different mechanisms explaining how the material is worn away from the surface were proposed: regardless of the mechanism, the forces generated for the duration of the affect between the surface and the particles are liable for its removing. Within the case of ductile surfaces, elastic and plastic traces could occur, relying on whether the substances yield strength is surpassed or no longer at any factor during have an impact on. For brittle substances, one-of-a-kind modes of crack formation make contributions to the loss of material by erosion [3]. Moreover, the collision of hard particles with a sample of brittle material at angles just about 90^o results in the growth of radial cracks around damaged areas on the brittle surface [4].The erosion system is brought about through many reasons, amongst them: (i) flow and environmental conditions: the impingement angle, particle velocity, temperature, impingement particles per unit time and presence of corrosive agents: (ii) Impingement particles properties: size, shape, density, hardness and friability: (iii) surface properties: topology, roughness, stress degree and hardness,[5] for illustration. A highly significant variable is the angle at which the particle hits the surface. For ductile metals and brittle solids, different erosion curves are obtained as a function of this impingement angle [6].

This paper reports the study of effects of protecting coatings used to remove wear forces so as to optimize the performance of equipment's parts subjected to excessive temperature erosive wear forces, increasing their service existence and diminishing maintenance costs. By using techniques such as high velocity oxygen fuel (HVOF), it is possible to coat components with materials that are more resistant to attack by corrosion and /or erosive wear.. The high velocity oxygen fuel (HVOF) system belongs to the family of thermal spraying procedures, and is extensively utilized in many industries to guard the add-ons against erosion. [7][8] Reported that the wear and tear resistance of self-fluxing alloys (NiCrBSic) coatings will also be generally extended by using including refractory carbides comparable to WC,VC,WC-Co, TiC, and Crc to the metal matrix. WC-Co coatings are commonly utilized in applications that require abrasive wear resistance. In the present investigation, the blend of Ni-alloy with WC-Co has been HVOF sprayed on SS-310 metal substrate; a laboratory-scale evaluation must be performed to ensure that the coatings behavior is predictable under real service conations. The deposited coatings are characterized based on the microstructure and physical properties.

2.0 EXPERIMENTAL PROCEDURE

2.1 Substrate material and development of coating

SS-310 steel is used as material for boiler tubes in some coal fire thermal plant. The specimen with dimension of 25 mm x 25 mm x8 mm were cut and grinded with SiC papers down to 180 grit before being HVOF sprayed to develop better adhesion between the substrate and the coating. The composite coating powder of 35 WC-Co/ NiCrBSi was used to spray to deposit coatings using HVOF process. HVOF spraying was carried out using a JP5000 equipment (Spraymet, Bangalore, India). The spraying parameters employed during HVOF deposition are listed in Table 1.

2.2 Powder and Coating Characterization Techniques

The surface and cross-section of the coated samples were wheel cloth polished for metallurgical examination. Zeiss Axiovert 200 MAT inverted optical microscope, fitted with image analyzing software Zeiss Axiovision Release 4.1 was used for optical microscopy. Porosity and average coating thickness was measured with this image analyzing software. Surface roughness of the coatings was recorded with Taylor Hobson optical Profilometerusing Surtronic 25 software.

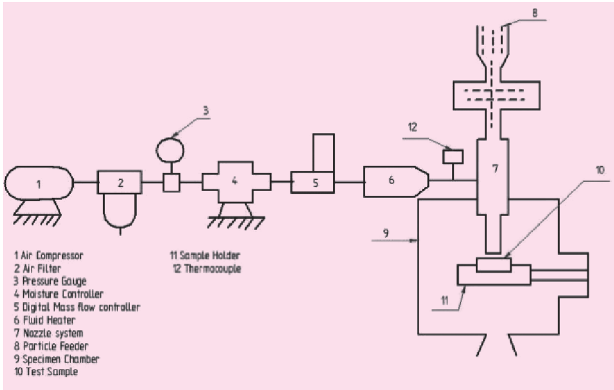


FIG. 1 SCHEMATIC VIEW OF HIGH TEMPERATURE AIR JET EROSION TEST RIG

TABLE 1

SPRAY PARAMETERS EMPLOYED FOR HVOF SPRAY PROCESS

JP5000HVOF, Powder : Praxair 1350 VM Size: -45 to +16 μm

1	Oxygen flow rate@210 PSIG, SCFH	1850
2	Fuel: Kerosene @170 PSIG, SCFH	5.8
3	Carrier gas flow(N2) @ 50 PSIG, SCFH	23
4	Stand off distance, inch	15
5	Powder feed rate, g/min	90
6	Thickness of deposit per pass	15
7	Particle velocity, m/s	740

Vickers micro-hardness measurements using 2.94 N were performed in order to assess the hardness across the coating and to ascertain substrate plastic strain hardening promoted by the high velocity projection. The powder and coatings were both investigated by X-ray diffraction using X-Pert Pro PAN alytical diffractometer with Cu target and surface morphology using scanning electron microscope (LEICA S440I) with EDAX attachment.

2.3 Erosion Studies

Erosion test was carried out using air jet erosion test rig (Figure 1) as per ASTM G76-02 standard. The erosion studies were performed on uncoated as well as coated samples for the purpose of comparison. The erosion test conditions utilized in the present study are listed in Table 2. The velocity of the eroding particles was determined by a rotating double-disc method as described by Ruff and Ives [9].

TABLE 2

EROSION TEST CONDITIONS

Erodent material	Silica sand angular)
Erodent size (AFS)	70
Erodent average hardness	880 HV
Particle velocity (m/s)	32
Erodent feed rate (g/min)	142.857
Impact angle (Deg)	30 and 90
Test temperature	Room and High Temperature(300 and 700^{o} C)
Test time (min)	7
Sample size (mm)	25 x 25x 8
Nozzle diameter (mm)	5
Stand off distance (mm)	10

The sample was first cleaned in acetone using an ultrasonic cleaner, dried and then weighed using an electronic balance with lease count of 0.01mg. The sample was then fixed to the sample holder of the erosion test righ and eroded with silica sand at the predetermined particle feed rate, impact velocity and impact angle for a period of about 7 min. The sample was then removed, cleaned in acetone and dried and weighed to determine the weight loss. This weight loss normalized by the mass of the silica particles causing the weight loss was then computed as the dimensionless incremental erosion rate.

3.0 RESULTS AND DISCUSSION

3.1 MORPHOLOGY OF COATING POWDERS

The morphology of the coating powders has been evaluated using the scanning electron microscopy which is shown in Figure 2. It is found from this figure that the 35WC-Co/NiCrBSi Powder particles have spherical morphology. The nominal size distribution of the coating powder as provided by the manufacturer is in the range of -45 to +15 µm.

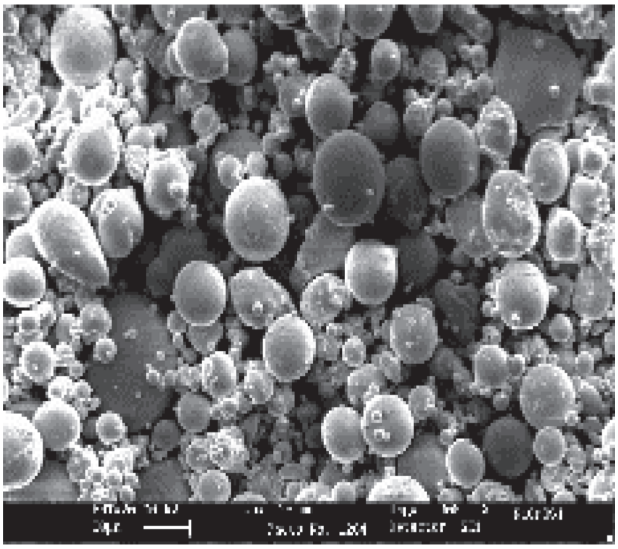


FIG. 2 SCANNING ELECTRON MICROGRAPH OF WC-CO/NICRBSI

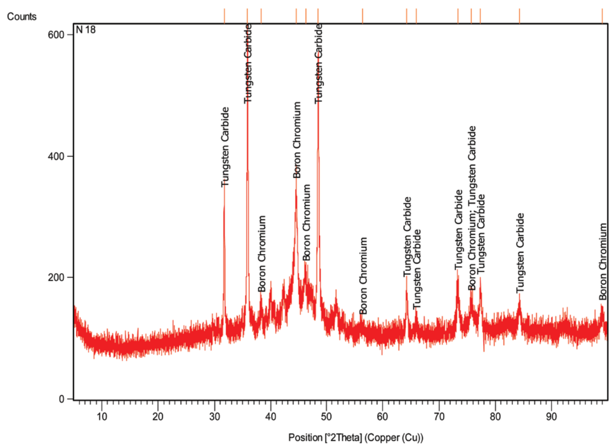


FIG. 3 X-RAY DIFFRACTION PATTERNS FOR POWDER

3.2 Phase Constitution of Powder and Coatings

The X-ray diffraction patterns for the surfaces of the HVOF sprayed 35 WC-Co/NiCrBSi coatings shown in Figure 3. The surface of the 35 WC-Co/NiCrBSi coating shows the presence of weak intensity peaks indexed to W2C phase. Generally, the formation of W2C phase is regarded as a product of decarburization in the thermal spraying. During the HVOF spraying, the flame temperature is usually less than 3000 deg C, and the particle speed can reach up to 800-1000 m/s. Therefore, the time of powder exposed to air is so short that the decomposition and decarburization of WC are not serious. The HVOF spraying parameter adopted resulted in high retention of WC in the matrix.

3.3 Coating Structure and Properties

The maximum value of porosity measured along the corss-sectional area using image analyzer software, found to be less then 0.5%. The lower value of porosity obtained for the HVOF sprayed coatings may be related to higher kinetic energies of powder particles and to the melting behavior exhibited by the particles. The partially melted particles form an almost porosity-free coating when they reach the substrate at high velocity. The measured values of the porosities are in good agreement with the finding of [10] and [11] for the HVOF sprayed composite coatings with nickel-based self-fluxing alloy and a WC hard phase. The average thickness of the coating deposted on the steel substrate was found to be 886 µm Figure 4. For the HVOF sprayed nickel-based coating, the typical coating thickness are in the range of 250-300 µm as suggested by [12] and [13] The average roughness value Ra of the coating is 7 µm.

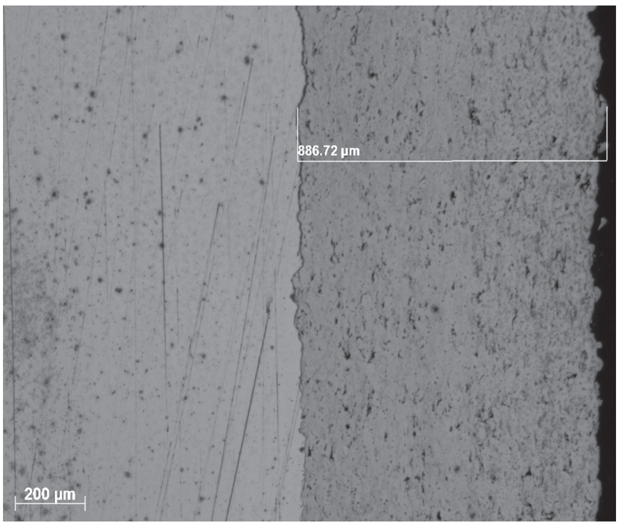


FIG. 4 THICKNESS OF COATING ON THE BASE PLATE

3.4 Erosion rate as a Function of Impingement Angle

The photographs showing the erosion scar produced on the eroded surface at different impact angles of 30 and 90 deg are shown in Figure 5. The central portion of the eroded scar represent localized region of material removal which is surrounded by region of elastically loaded material. The erosion rate curves along the bar chart indicating the volumetric steady state wear loss. The steady state erosion rate of the uncoated SS-310 steel at 30 deg impingement is higher than that at 90 deg impact angle which is a characteristic behavior of the ductile materials, where material removal takes place predominatly by plastic deformation. In general, the incremental erosion rate curves follow the same form as that for the ductile steels at 90 deg, having a low initial rate, reaching a peak after 50 g of impacting particles and, subsequently, reaching a steady state erosion rate which is considerably lower than the peak rate [14] and [15].

30° Impact angle	90° Impact angle

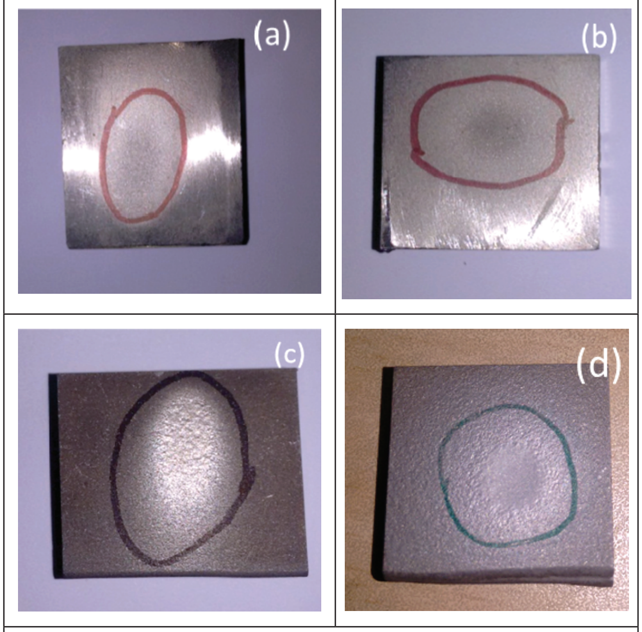


FIG. 5 CAMERA MACROGRAPH SHOWING THE EROSION SCAR AT 400° C PRODUCED ON THE SURFACE AT AN IMPACT ANGLE OF 30 DEG AND 90 DEG (NOT IN SCALE)(A) AND (B) UNCOATED STEEL (C) AND (D) WC-CO/NICRBSI

3.4.1 Erosion Resistance of Wc-Co/Nicrbsi Coatings

Figure 6 shows the effect of impingement angle and erosion temperature on the erosion rates of 35WC-Co/NiCrBSi coatings. As shown in Figure 7 the erosion rates of 35WC-Co/NiCrBSi coating increases firstly and then decreases with the increase of the erosion temperature, and the maximum erosion occurs at 700° C. The phenomenon can be interpreted as follows: the matrix of material softens gradually with increasing temperature and the hardness of materials is reduced, thereby leading to the high erosion rates at 700° C. As shown in Figure 8 the erosion rate of 35WC-Co/NiCrBSi largely relies on the impingment angle. 35WC-Co/NiCrBSi coatings exemplify brittle behavior as a function of impact angle, where it exhibit higher wear rate at 90° impact angle. It increases gradually with incrase of the impingment angle and reaches the maximum value at 90°.

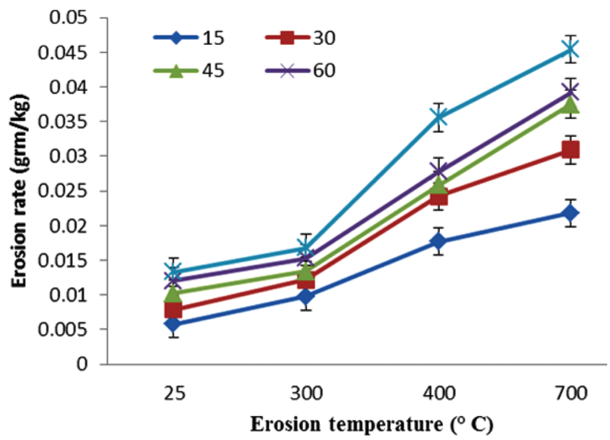


FIG. 6 THE EROSION RATE OF 35WC- CO/NICRBSI COATING WITH RESPECT TO THE EROSION TEMPERATURE AND IMPINGEMENT ANGLE.

The kinetic energy of erosion particles impacting on the target surface at 90° is much higher than that for oblique erosion, which caused the maximum erosion rate at 90°.

3.4.2 Erosion rate as a Function of Impingement Angle

However the difference in magnitude of steady state erosion rates at 30 deg and 90 deg impact angles is marginal and lies in a narrow range and hence it may not be conclusive in predictiong the ductile or brittle nature of the coating. [16] and [17] reported that the anglular dependence of erosion is not a characteristic of the material alone, but depends also on the conditions of erosion and hence suggest that the terms brittle and ductile in the context of erosion should therefore be used with caution. This lead to the further detailed microscopic analysis. The Uncoated SS-310 steel exhibit higher erosion rate at Room Temperature as seen from Figure (7) when compared to 35WC-Co/NiCrBSi, this may be due to WC-Co offer the greatest wear resistance at ambient temperature.

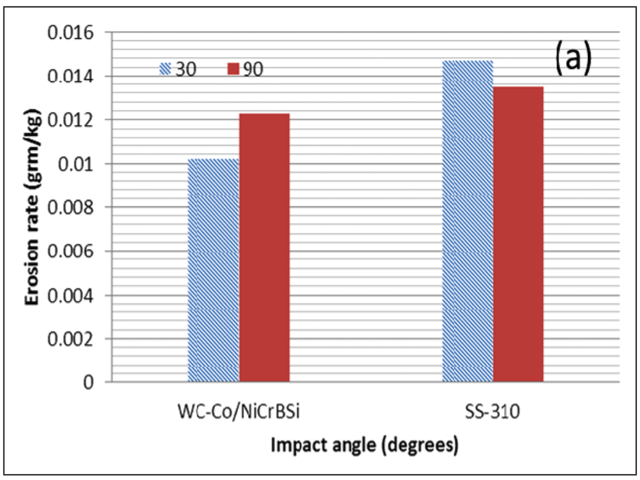
From the Figure 7 (b) we observe that there is drastic change in erosion rate from room temperature to higher temperature (400^{o} C). The erosion rate of WC-Co/NiCrBSi coating is about 1.5 times higher at 30 deg impact angle when compare to bare SS-310 steel, similarly at 90 deg impact angle WC-Co-NiCrBSi is about 2 times higher then SS-310 steel, this indicates erosion sensitivity is higher at 90 deg impact angle and also the temperature effect. Similarly From the Figure 8 (c) we observe that erosion rate at a higher temperature (700^{o} C) WC-Co/NiCrBSi coating is about 3 times higher at 30 deg impact angle when compare to bare SS-310 steel, similarly at 90 deg impact angle WC-Co/NiCrBSi is about 2 times higher then SS-310 steel, this indicates erosion sensitivity to higher temperature effects.

Figure 8 (a) and (b) shows the change in erosion behavior with change in the temperature. It is observe that WC-Co/NiCrBSi shows least erosion rate (maximum erosion resistance) at room temperature to 300° C in both 30 and 90 deg impact angle when compare to bare SS-310 steel, however at 300° C there is a drastic change in erosion rate, there is a predominatly increase in erosion rate up to 700° C. WC-Co/NiCrBSi offers the greatest wear resistance at ambient temperature, its poor performance limits its application to temperatures below 200-300° C.

4.0 EROSION MECHANISM

The SEM micrograhas on the surface of the eroded SS-310 clearly show the embedment of sand particle and the wear mechanism essentially involves the indentaion induced several plastic deformation.

Figure 9 a-b present the wear mechanisms involved in this study on stainless steels 310 at room temperature similarly Figure 9 c-d present the wear mechanisms at 700° C, From the Figure 6 (a) we observe that larger Slip band are clearly seen on the surface at 30° with some wear debris inside, whereas in Figure 9 (b) a more Crater with roughened surface is observed at 90° with some lip formation on the surfaces near to the crater. Figure 9 (c) at 700° C temperature exhibit Ploughing action seen on the surface at 30° and more erosion rate. On the other hand, Figure 9 (d) showed pitting, chips removal and smeared wear debris at 90° and also fragments of abrasive particles embedded or smeared on the surface were clearly seen at angles 90°. The reduction in mass loss at higher impact angles, near or at 90°, is because there was not too much evidence of sliding action of abrasive particles unlike lower impact angles where the sliding component is significant and increases the mass lost in the material.



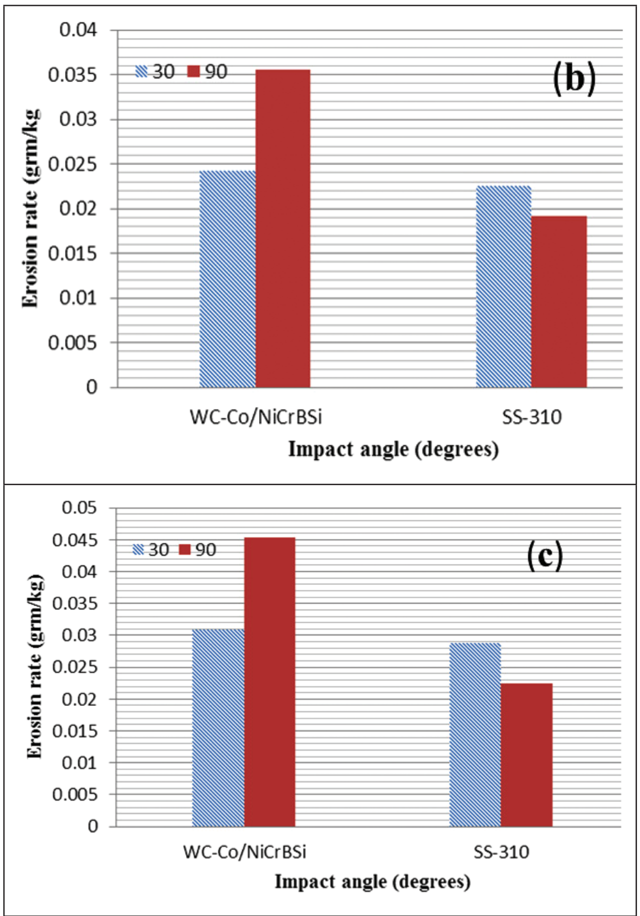
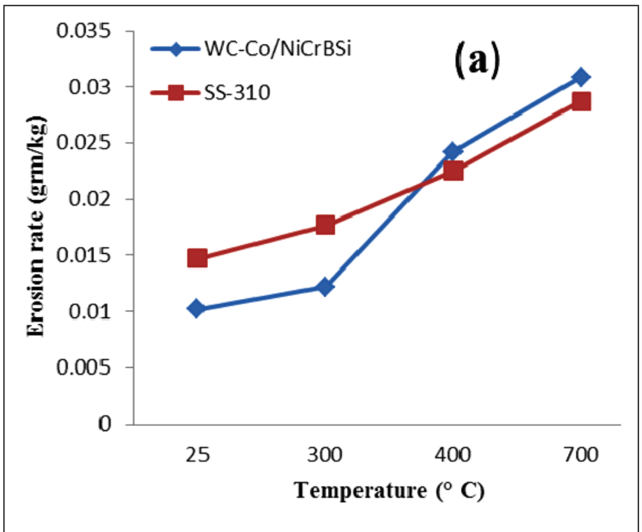
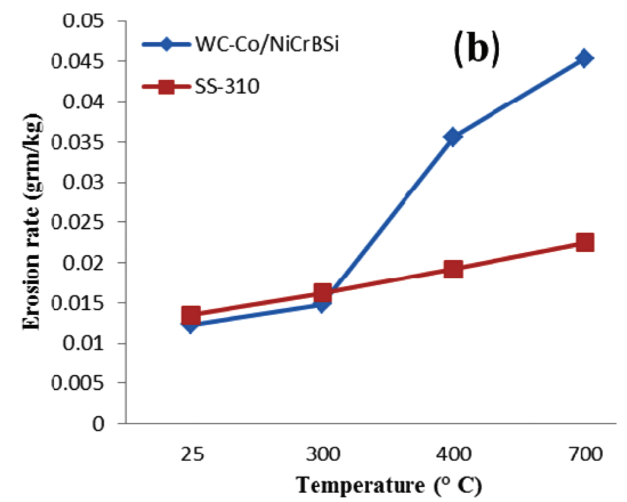


FIG. 7 HISTOGRAM ILLUSTRATING THE STEADY STATE EROSION RATE OF SS-310 (UNCOATED) AND WC-CO/NICRBSI COATED STEEL AT 30 AND 90 DEG IMPACT ANGLE FOR DIFFERENT TEMPERATURE RANGES (A)ROOM TEMPERATURE (25OC), (B) 400OC AND (C) 700OC TEMPERATURE.

3.4.3 Erosion rate as a Fuction of Temperature: At 30 And 90 Deg Impact Angle



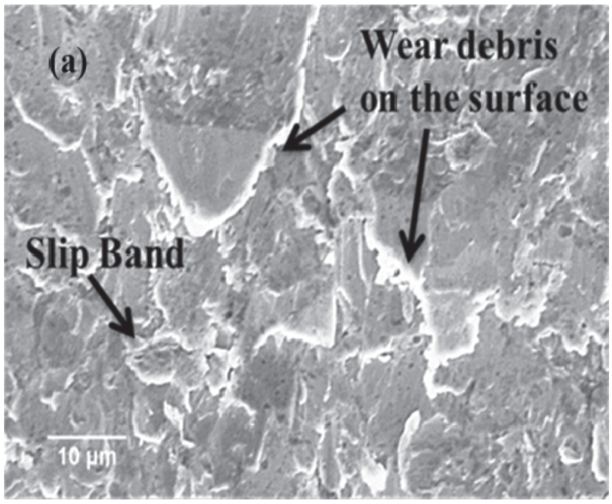
At 30 deg Impact Angle



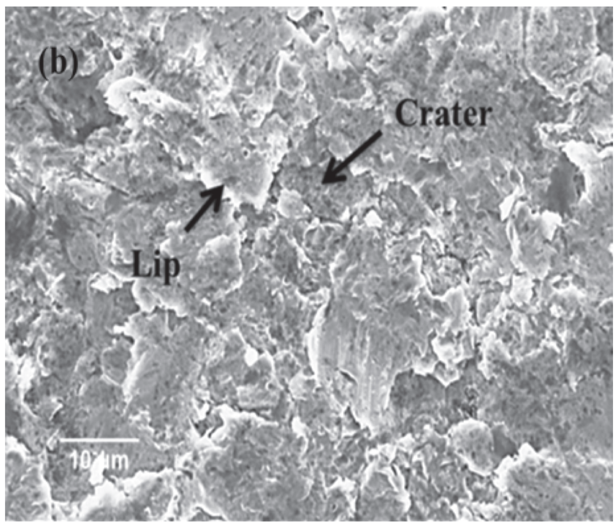
At 90 deg Impact Angle

FIG. 8 VARIATION OF EROSION RATE WITH TEMPERATURE FOR WC-CO-NICRBSI AND SS-310 STEEL (A IMPINGMENT ANGLE OF 30O AND (B) IMPINGMENT ANGLE OF 90° , IMPINGEMENT VELOCITY 32 M/S.

30 IMPACT ANGLE



90 IMPACT ANGLE



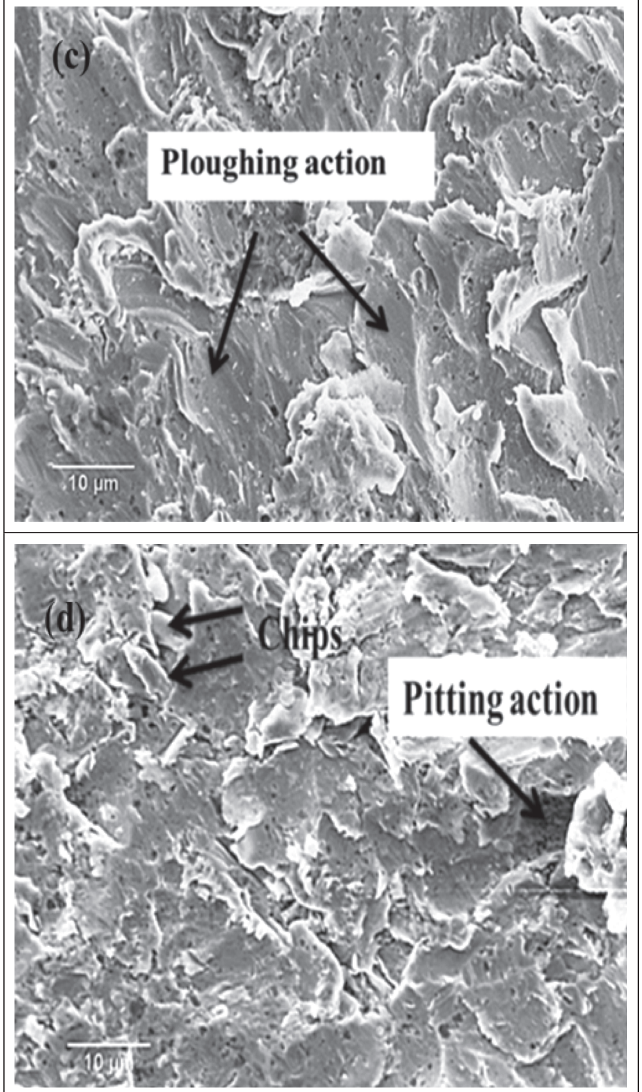
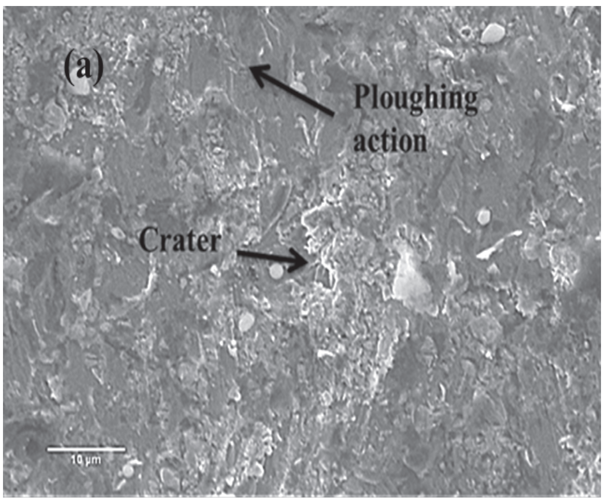


FIG. 9 SEM MICROGRAPHS SHOWING ERODED SURFACE MORPHOLOGY OF SS-310 STEEL AT 30°AND 90° IMPACT ANGLES. DIRECTION OF PARTICLE IMPINGMENT IS FROM TOP TO BOTTOM OF MIROCGRAPHS. (A) AND (B) SHOWS SURFACE ERODED AT 25° C AND (C) & (D) SHOWS SURFACE ERODED AT 700° C.



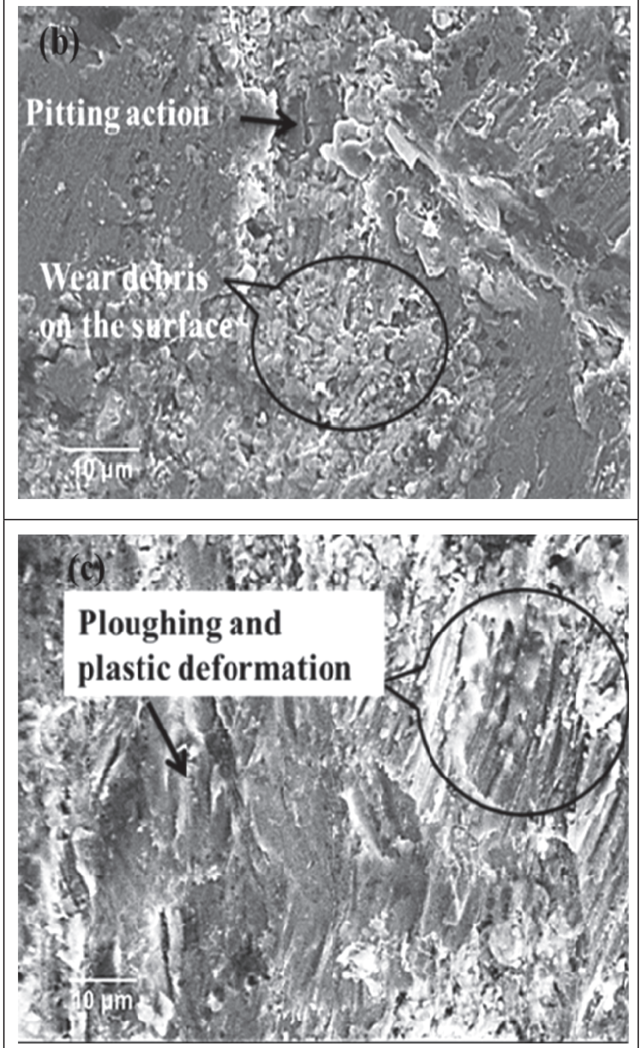


FIG. 10 SEM MICROGRAPHS SHOWING THE ERODED SURFACE MORPHOLOGY WC-CO-NICRBSI COATING AT 30° IMPACT ANGLES. DIRECTION OF PARTICLE IMPINGMENT IS FROM TOP TO BOTTOM OF MIROCGRAPHS. (A) 25° C (B) 400° C AND (C) AT 700° C.

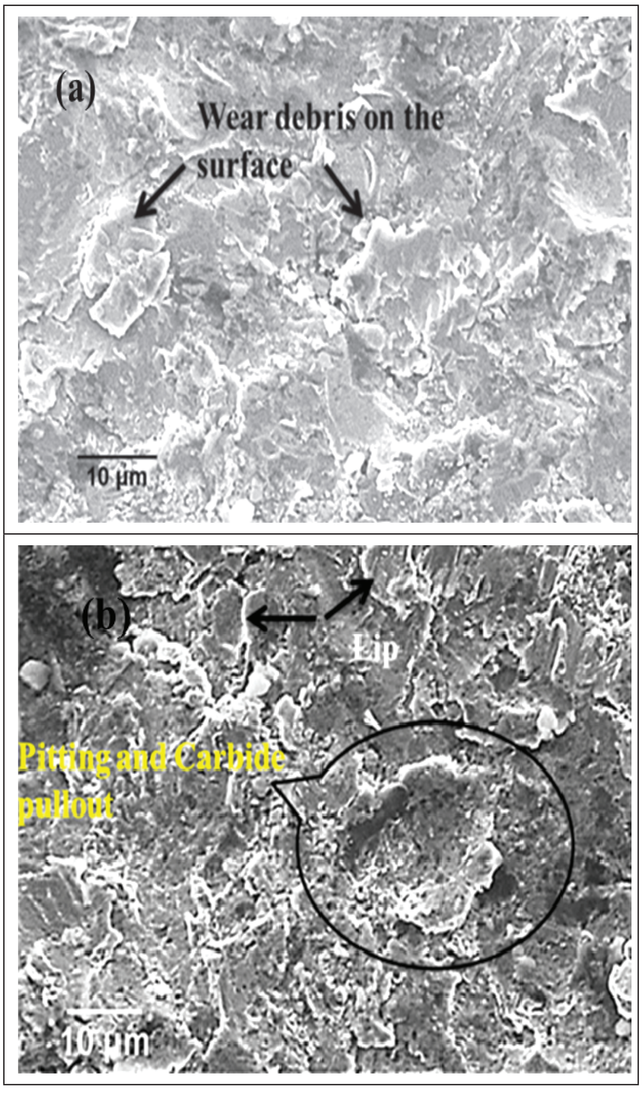
Figure 10 (a) shows the erosion morphologies of the matrix in WC-Co/NiCrBSi coating eroded at 30° impact angle for room temperature (25 deg C) shows ploughing action and Craters due to impact of silica particle, the erosion rate is lower at room temperature as the temperature reaches near about 300 to 400° C Figure 10 (b) the erosion loss predominatly increases we may observe morphology with number Pitting action and Wear debris on the surface, this indicates the carbide removal, as the temperature futher increase up to 700° C Figure 10 (c) we observe of groves and lips which indicated the material removal by ploughing and cutting mechanism.

Material loss is in the form of platelets by repeated impact of erodent. It is apparent from the micrograph that groove might have formed predominatly in the softer binder region, lead to dislocation of hard WC particles. The grooves in the binder region act as failure initating concentrators and small carbide grains crumble off uncrushed, whereas the main mechanism of large grains failure is by chipping [18].

The coating eroded at 90° impact angle showed a surface morphology Figure 11 with a numerous crater formed by impacting silica erodent. The groove marked in Figure 10(c) shows the evidence of carbide particle pull out and gross spalling of the coating. Craters formed are surrounded by lips suggesting strain localization which is common feature in ductile erosion mode Figure (b). Such ductile extrusion of material migh have predominantly occurred in the softer nickel-based metallic binder matrix. The surface roughness of the coating eroded at 30° and 90° impact angle is found to be 2.9 and 4.5 µm respectively. Consequently the morphology of the eroded surface indicates craters, grooves formed in binder matrix characterized by lips at their rim, platelet formation and carbide particle pull out as the existing erosion mechanism. These mechanisms signify composite ductile and brittle modes of erosion, although the brittle mode is dominant. [18], [19] and [20] also observed combination of ductile and brittle mode of erosion with WC-Co hard metals and coatings and titanim carbide base cermets.

5.0 CONCLUSION

- At room temperature HVOF sprayed 35WC-Co/NiCrBSi coatings has been proven to be very promising when compared with SS-310 stainless steel.
- 35WC-Co/NiCrBSi offers the greatest wear resistance at ambient temperature, however, its poor performance limits its application to temperatures above 300-350° C.
- The erosion rate of 35WC-Co/NiCrBSi largely relies on the Temperature and impingment angle. Erosion rate increases gradually with increase of temperature (25-700° C) and the impingment angle reaches the maximum value at 90°. The kinetic energy of erosion particles impacting on the target surface at 90° is much higher than that for oblique erosion, which caused the maximum erosion rate at 90°.
- The brittle erosion mechanisms dominate the material removal due to solid particle erosion-wear at higher temperature, and the removal of materials are mainly caused by brittle fracture and stripping of aggregates because of losing the protection from the matrix. The primary erosion mechanisms of materials at high temperature are due to plastic deformation.



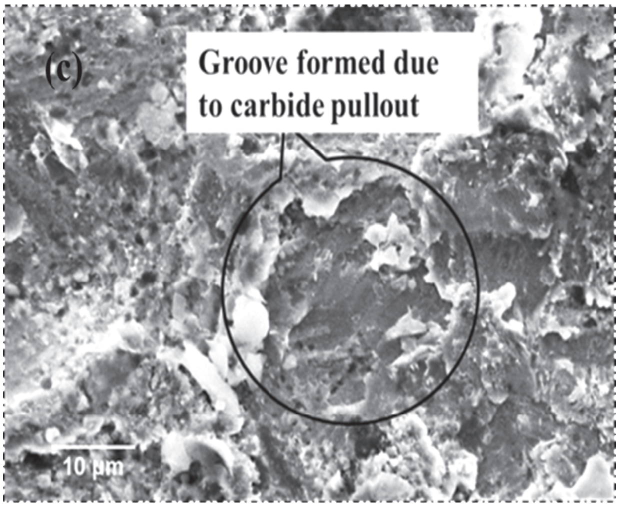


FIG. 11 SEM MICROGRAPHS SHOWING THE ERODED SURFACE MORPHOLOGY WC-CO/NICRBSI COATINGAT 90° IMPACT ANGLES DIRECTION OF PARTICLE IMPINGMENT IS FROM TOP TO BOTTOM OF MIROCGRAPHS. (A) 25° C (B) 400° C AND (C) AT 700° C.

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