Journal of Engineering Science and Technology
Vol. 17, No. 1 (2022) 0379 - 0390

ENHANCING THE PERFORMANCE OF INCONEL 601 ALLOY BY EROSION RESISTANT WC-CR-CO COATED MATERIAL

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Abstract

Thermal barrier coatings are advanced material systems usually applied on metallic surfaces to protect against elevated operating temperatures. To protect the substrate from thermally induced damage, the barrier thickness should be maintained and the factors affecting this are erosion, corrosion, and foreign object damage. The erosion problems can be prevented by Tungsten carbide (WC), Cobalt (Co), and Chromium (Cr) coated on Inconel 601 as a substrate with a constant mesh size of 27.5 μm by High Velocity Oxygen-Fuel (HVOF) technique. Tungsten carbide coatings exhibit good resistance to wear, erosion-corrosion, and hardness which increases the service life of parts when surfaces are exposed to high temperatures. The solid particle erosion study was conducted using an air jet erosion test rig at a velocity of 70 m/s and impingement angle 30°, 60°, 75° and 90°, on HVOF spray coated steel at 750°C. The erosion rate of tungsten carbide coated material is minimum at various impingement angles, the best erosion resistant coating composition is suggested for high temperature applications. The microstructure, composition, and phases present in the coatings on Inconel 601 were examined by Scanning Electron Microscope and X-Ray Diffraction. Experimental data from erosion, the erosion rate (3.2×102 mg/kg) is very minimum for the coating sample WC-11Co-2Cr at 30º angle of impingement and hardness test results were conclusive indicating high microhardness for the WC-11Co-2Cr coatings.

Keywords: Gas turbine, High velocity, HVOF spray, Oxy-fuel, Thermal barrier coating.

1. Introduction

The gas turbine is a continuous combustion turbine that is driven by expanding high temperature gases by combustion of fuel as in the jet engine. Gas turbines operate at high temperatures as high as 1260°C hence the need for internal cooling for turbine parts becomes crucial [1]. Thermal Barrier Coating (TBCs) prepared for low thermal conductivity ceramic composite will have increasing use in gas turbine engines to give thermal insulation to the components as of hot gases in the engines use for aircraft propulsion, generation of power, and marine propulsion. The superalloy components are used as TBCs with internal cooling, provides temperature reduced up to 300 K components of superalloy surface. This enables engines to work at temperatures greater than the melting temperature of the superalloy, meaning this improving the energy competence and performance of engines. TBCs give to dipping the metal temperature, thus increases the duration capability of parts. TBC's are susceptible to various life restrictive issues associate with their working environment with erosion, corrosion, oxidation, and distant object scratch. In this present work, the coating composition of tungsten carbide with cobalt and chromium are varied and the erosion and microhardness tests were conducted.

Li et al. [1] obtained the erosion behavior of three WC-Co-Cr coatings by high velocity oxy-fuel/air-fuel (HVOF/HVAF) thermal spray systems has been investigated using Al_2O_3 as erodent at four impingement angles (15°, 45°, 75°, 90°) and 90 m/s impact velocity. The results indicate that the micro-cutting and coatings spallation is the main erosion mechanisms for coatings and the proportion of the two mechanisms changes depending on the impingement angle.

Richert [2] carried out a comparison of wear resistance of Tungsten carbide(WC), Chromium carbide (Cr_3C_2) and its compositions, thermally sprayed using HVOF and plasma spraying technique. The microstructures of all coatings were studied by optical microscopy and disperse spectrometer (EDS) for recognition of chemical composition in micro areas of layers and results showed that High Velocity Oxy-Fuel coatings prove more unvarying and fine-grained microstructure than plasma sprayed coatings and concluded that wear resistance vigorously depends on internal microstructures of coatings.

Hajare and Gogte [3] evaluated the coatings of WC and CrC sprayed by HVOF thermal spraying process, both coating compositions comprised of cobalt as a binder with the same percentage. The mechanical characterizations of the considered coatings were evaluated as per the ASTM G99. Considering varying loads, from the results, the wear rate of WC carbide coating lower than that of Cr carbide coating.

Wielage et al. [4] compared abrasive wear resistance of tungsten carbide coated using HVOF and APS thermal spraying and also electroplated hard chromium coating. The influence of abrasive wheels on mass loss in the Taber abraser test was studied for HVOF sprayed coatings. Among the considered cermet materials 86WC-10Co-4Cr proved to be the best performing based on wear resistance. The coatings have an important role in the functioning of insulating parts, like gas turbine blades and aero-engine components working at high temperatures. Thermal Barrier Coatings have finished possibly increase the service temperature of gas turbines. However erosive solid particles formed during the combustion process, from the burning of unlike types of heavy oils or synthetic fuels and various operating conditions hinder or reduce the operating life of TBC [4-6].

Behera et al. [5] in their experimental analysis carried out air jet erosion testing on fly-ash combined with quartz and ilmenite powder in a variety of mass proportions thermally sprayed on mild steel and copper base materials. Silica erodent of size 150-250 µm is used in erosion test by Air Jet erosion tester (As per ASTM G76). The results confirmed that erosion wear is powerfully influenced by the size of erodent, impingement velocity, impingement angle, standoff distance, and microhardness. The highest erosion occurs at a normal angle of Impingement. Also observed that air jet erosion [7, 8] system initiates through plastic deformation.

The materials that consist of both brittle and ductile constituents can show erosion behavior as ductile or a brittle manner. The high-velocity oxy-fuel (HVOF) sprayed WC-Co/NiCrFeSiB coatings on GrA1 boiler tube steel exhibit composite ductile and brittle type of erosion under angular silica sand erodent of size 125-180 µm impingement at 40 m/s. The HVOF spraying tops to high retention of WC in the coating matrix complemented with lower porosity. The as-sprayed, as well as eroded coatings, have been observed using Scanning Electron Microscope and Optical Profilometer [9].

The objective is to find the best specialized coating material which will work under standard operating conditions. The specimens of different specialized coatings were prepared by Thermal Spray Coating Technique [10, 11]. The coating thickness is constant throughout the base material surface and the erosion test conducted in a very high temperature environment. The prepared specimens are tested using an erosion tester considering various parameters such as temperature, the velocity of the gas, angle of impingement, and testing duration. Also, to study the surface morphology of the eroded surface of the coatings were observed by Scanning Electronic Microscope (SEM). Based on the test results obtained, the best-specialized coating material suitable for Gas Turbine Blades application is suggested. From the above literature review, it is observed that the erosion rate test is not conducted at elevated temperature with the addition of Cobal and Chromium.

2. Materials Details

2.1. Selection of coating material

Three coating materials Tungsten carbide (WC), Cobalt (Co), and Chromium (Cr) of varying composition were chosen for the study. Tungsten carbide coatings have excellent resistance to sliding wear, erosion, abrasion, and cavitation. The coating compositions are chosen as shown in Table 1.

Table 1. Composition of coating material.

Coating Samples	Nominal Composition	Powder type	Average size of powder (µm)
A	WC-8Co-2Cr	Blend	27.5
B	WC-11Co-2Cr	Blend	27.5
C	WC-14Co-2Cr	Blend	27.5

2.2. Selection of substrate/base metal

The coating was done on Inconel-601, a nickel/chromium/iron alloy 601. The substrate material is used for general purposes production material with applications that require resistance to heat and corrosion. The alloy also has high corrosion resistance, has good mechanical strength, and is formed, machined, and welded. An excellent characteristic of Inconel alloy 601 is resistance to high temperature oxidation. The chemical composition of Inconel-601 is tabulated in Table 2.

Table 2. Chemical composition of Inconel-601

Elements	Ni	Cr	S	Mn	Al	C	Cu	Si	Fe
Max. %	58	21	-	-	1	-	-	-	Bal.
Min. %	63	25	0.015	1	1.7	0.1	1	0.5	

3. Experimental Procedure

3.1. Sample preparation

The base material Inconel 601 is prepared with the dimensions 24.5×24.5×5 mm by Electron Discharge Machining process (wire cutting). Grinding and cleaning were performed before the coating process is taken up. Figure 1(a) shows the base material of Inconel 601 is mixture of nickel-chromium applications that required resistance to heat, and corrosion used for the coating and Melting temperature is 1320°C - 1370° C. Figure 1(b) shows the WC-8 Co-2Cr coated on the substrate material using high Velocity Oxy-Fuel (HVOF) spray technique.

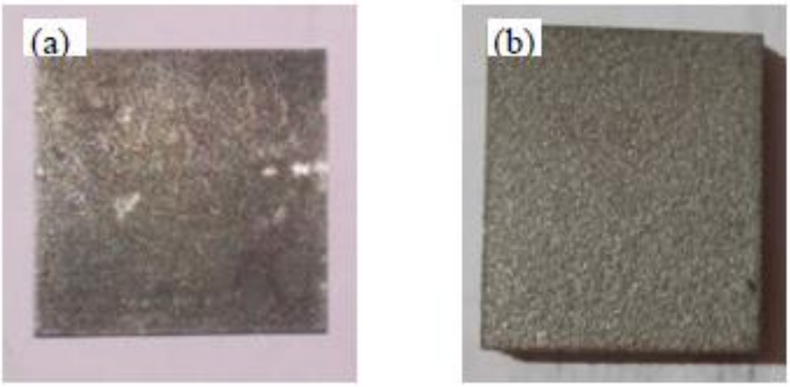

Fig. 1. (a) Base metal Inconel 601, (b) WC-8Co-2Cr coated specimen.

3.2. Formation of coating using HVOF process

WC based coating is used for the HVOF coatings. In the High Velocity Oxygen Fuel (HVOF) technique, the powder is supplied axially to the chamber inside a gas flame is continuously burning with maximum pressure. Exhaust gas passes through the expansion nozzle and produces a maximum velocity gas stream (60 m/s). In a gas stream, the powder particles were heated with the temperature of

3000°C transferred by kinetic energy to the substrate surface, making a thick coating with a thickness of 200 microns [12]. The substrates were mounted on a table holder apart from a distance of 6 to 8 inches and impingement velocity 1000 m/s. coatings were deposited on (24.5×24.5×5) mm size Inconel substrate. The coatings were melted using an acetylene-oxygen flame torch. Fusing and cooling were performed in the air. The coatings are prepared using the HOVF spray technique using 80 kW capacity. Initially, the base metal is grit blasted with a pressure of 3 kg/cm^2 with Aluminium Oxide having a size of 60 μm for the average roughness of the surface was 6.8 μ. The stand-off distance in the blast was kept between 120-150 mm. Sandblasted specimens were washed with acetone in ultrasonic cleaning.

3.3. Scanning electron microscope

Figures 2(a), (b), and (c) shows the microstructure features of WC-Co-Cr based coating on Inconel 601 substrate. The surface morphology of coating shows that the uniform distribution of WC, Co, Cr, and superior interfacial bonding. Especially the coatings will have very low Porosity/Cracks were observed in all the composites of in the matrix alloy with better interfacial bonding.

The surface of a sample is relatively smooth, but it presents small white particles which are called cobalt phases and darker grey particles show the presence of tungsten carbide and the appearance of the small percentage of cracks is observed on the surface. The micrographs also showed ‘cracks’ between splats. It consists of a round circular shape structure that shows the presence of pure tungsten carbide with white particles which are called cobalt phases. The interface bond of the coated specimen depends on the coating microstructure and interparticle.

Sprayed coating microstructures were found to depend on the powder characteristics. The coatings have very fine, and it visibly shows the splat-structure in the micrographs. Non-crystalline binders at the margins of the spalts are shown by the higher magnification. All three coatings were observed to be full of compact areas of fine bonded tungsten particles and a small number of white particles representing cobalt phases as in, but they have areas inside which extremely small pores divide the grains from the binder. The bond between WC particle and matrix is further confirmed at higher magnification.

3.4. Erosion test

Air Jet Erosion Test (As per ASTM G76) [5] conducted for all the sample coatings, the schematic diagram of the Air Jet Erosion Test rig is shown in Fig. 3. Eroding particles used were alumina particles of size 50μm. The particle velocity was set up to 70 m/s, similarly, the operating temperature was fixed to 750ºC. The erosion test conducted with different angle of impingement is 30°, 60°, 75°, and 90° for each coating composition. The distance between specimen surface to the nozzle, (Standoff distance) was maintained at 10±1 mm. The duration of time considered was 10 minutes [5]. Mass loss was evaluated using an electronic weighing machine. The detailed test parameters were shown in below Table 3.

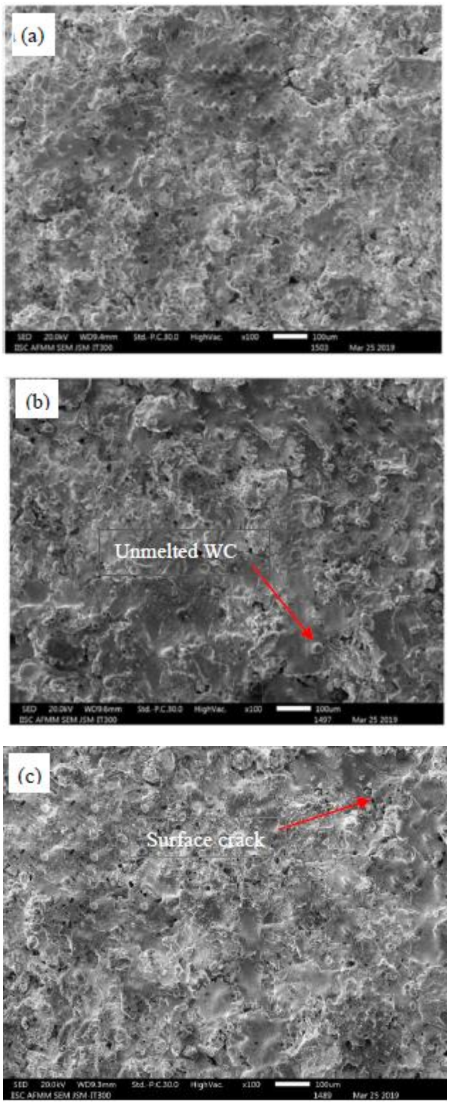

Fig. 2. SEM images of tungsten carbide (WC-Co-Cr) coatings deposited on base material Inconel-601. (a) WC-8Co-2Cr, (b) WC-11Co-2Cr, (c) WC-14Co-2Cr.

Table 3.The operating parameters of coating deposition.

Operating temperature	**750° C**
Impingement angle	30°, 60°, 75°, 90°
Particle velocity	70 m/s
Test duration	10 minutes
Nozzle tube inner diameter	1.5 mm ± 0.075 mm
Particle feed rate	2.0 ± 0.5 g/min^{-1}
Distance from specimen surface to nozzle	100 ± 1 mm
Eroding particle	50 μm size alumina

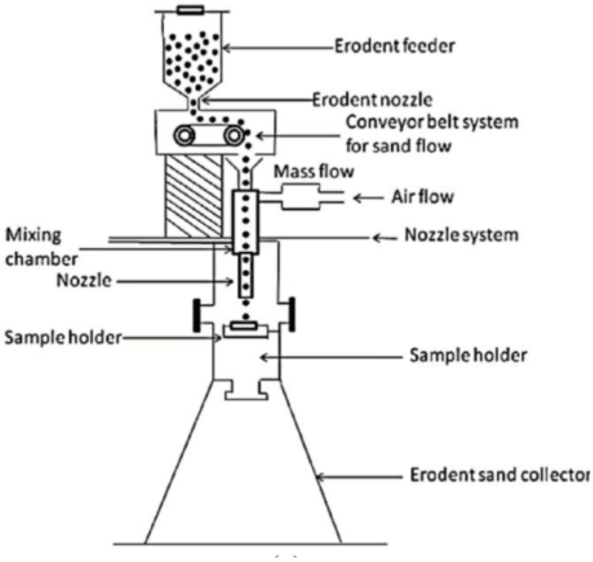

Fig. 3. Air jet erosion test rig [9].

4. Results and Discussion

The variation of erosion rate for three different coating compositions at different impingement angles is as shown in Fig. 4. The eroded surface of coating samples is as shown in Fig. 5. The erosion rate was found to increase with increasing impingement angle for all the coatings up to 75º and drastically decreases with a further increase in impingement angle. This may be due to a ploughing-cutting primarily through the splats quite at boundaries. The erosion rate(3.2 x10^2 mg/kg) is very minimum for the coating sample WC-11Co-2Cr at a 30º angle of impingement. The erosion rate is maximum for the sample WC-8Co-2Cr at 75º angle of impingement.

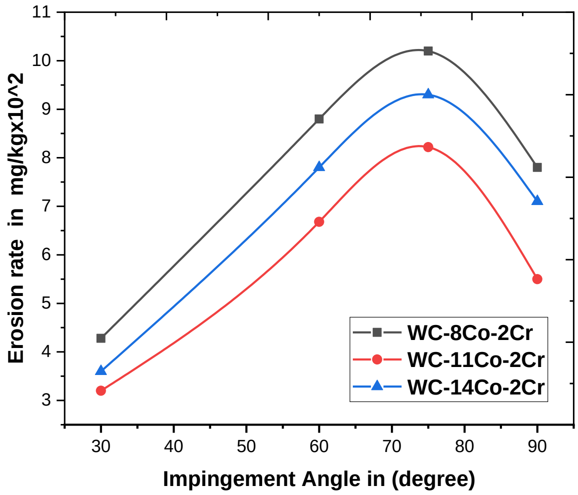

Fig. 4. Comparison of erosion rate vs. impingement angle.

Fig. 5. Eroded coating specimens.

The variations of erosion rate of all three different coating compositions at the same angle of impingement are shown in Fig. 6. It is observed that maximum erosion takes place at a normal Impingement angle. The maximum erosion rate was found to be 10.2 x10^2 mg/kg for WC-8Co-2Cr at 75º angle and the minimum erosion rate is observed in the coating WC-11Co-2Cr. The behavior is noticed in the brittle materials (WC coatings) everywhere the rate of erosion at all times increases with changing to higher impingement angles and attains a highest at normal (75°)impingement angle, in adding up to this, under brittle erosion situation the magnitude of erosion rate is calculated only by the normal component of impingement velocity.

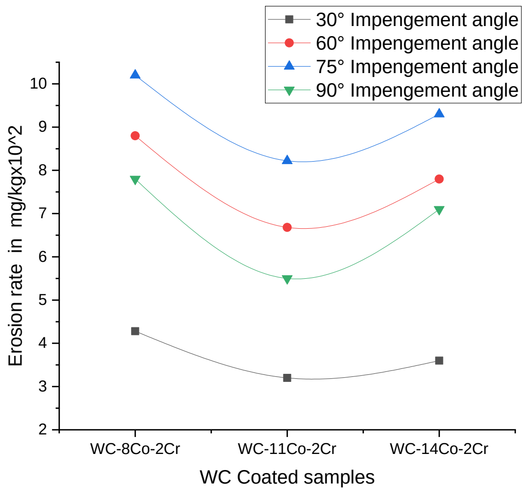

Fig. 6. Comparison of Erosion rate of coating samples at constant Impingement angle.

The erosion rate due to cutting wear, defined as the ratio of the mass of the material eroded from the target surface to mass of the impacting particle, is given by the following equation:

$$\varepsilon_c = \frac{m}{m_p} = \frac{K_c \rho_m \rho_p^{3/2} d_p^3 V^3 \sin^3\beta}{3^3 \sigma_y^{3/2}\left(\pi K_c \rho_p \frac{d_p^3}{6}\right)} = \frac{K_1 \rho_m \rho_p^{1/2} d_p^3 V^3 \sin^3\beta}{\sigma_y^{3/2}}$$

where m_p= the mass of a spherical particle, m=the mass of material eroded, d_p and ρ_p are the particle diameter and density, respectively, K_c = a constant, ρ_m = the density of target material, β = particle incident angle, σ_y =yield stress, and K_1 is a constant.

The Micro-hardness measurement is done using a Vickers microhardness tester for 9.81 N loads. It is observed that the micro-hardness of the WC-11Co-2Cr coatings was superior to WC-8Co-2Cr and WC-14Co-2Cr coatings (This validates the results obtained in the M W Richert's paper, i.e., The hardness influences the resistance against wear and erosion). Because of the high hardness in sample B (WC-11Co-2Cr) coating, a minimum erosion rate is observed. The results are depicted in Fig. 7. Micro-Hardness of WC-11Co-2Cr was found to be the highest. This may be due to good matrix alloy formation and proper interfacial bonding.

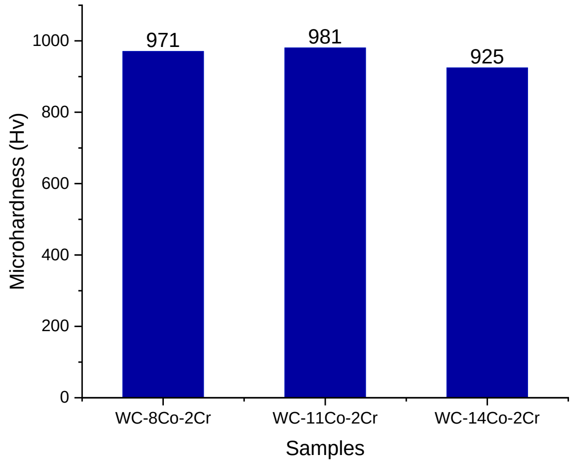

Fig. 7. Micro-hardness numbers of all compositions.

Figure 8 shows the surface morphology of the eroded surface of the fine powder mesh size coatings WC-11Co-2Cr with 90° impingement angle is observed by Scanning Electronic Microscope(SEM). The surface morphologies illustrate cracked and chipped morphology, indicating the brittle erosion mechanism. erosion wastages occurred by a large cracking and chipping mechanism of fractured and loosened pieces, the size of which is determined by the splat sizes of coatings. In the same micrographs, a fine size may view the cracking, deformation, and displacement of WC grains as well as the extrusion and favoured removal of the cobalt binder which is tag along by the loss of single unproven grains. The fine-grained materials also behave in a predominate brittle manner in which transgranular rupture of the WC grains and intergranular rupture [13, 14] within the cobalt binder phase predominates. In addition to this, the lips and ridges are created at some point in plastic deformation which provides a significant platelet mechanism that can be obtained.

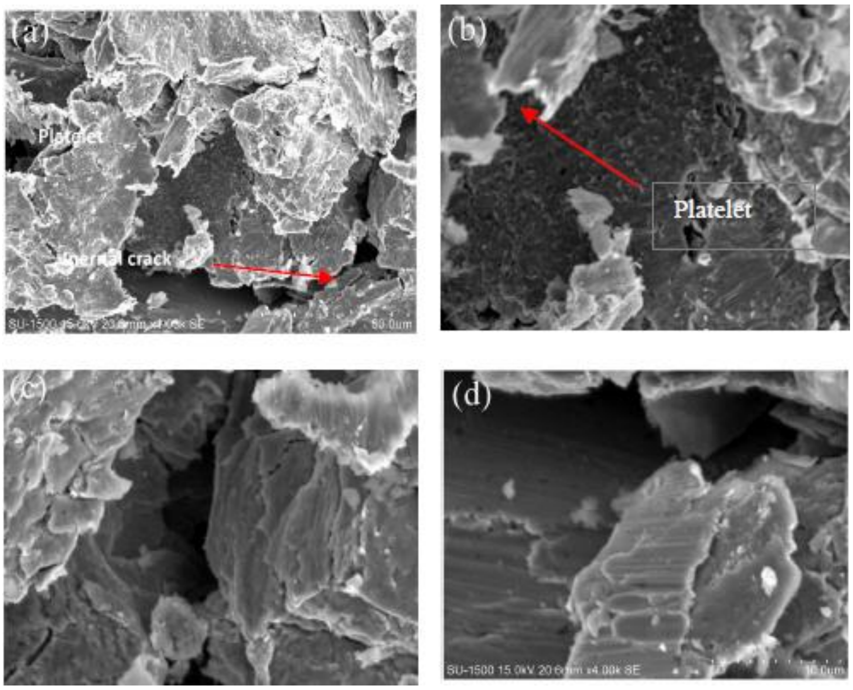

Fig. 8. SEM micrographs of eroded surfaces at 90° impingement of WC- 11Co-2Cr fine powder size 27.5 μm (a) 1000X, (b) 2000X, (c) 3000x and (d) 4000X.

Solid particle erosion is a wear process where particles strike against a surface and promote material loss as shown in Fig. 9. The surface of the less incident angle 60° coated material shows long, thin grooves and lipping. The surface of the intermediate incident angle 75° erosion coatings shows a combination of cut grooves and smear craters [9, 15-17]. The erosion is described by concentrated local plastic flow producing lips and ploughs on the subject of the crater periphery [18, 19]. Compare the results with Li et al. [1], the erosion behavior of three WC-Co-Cr coatings obtained by high velocity oxy-fuel/air-fuel gives better erosion results. The erosion behavior of three WC-Co-Cr coatings obtained by high velocity oxy-fuel/air-fuel. For the scope of the future work, variation of different weight percent of Cr coatings on the base materials and erosion test can be conducted at elevated temperature.

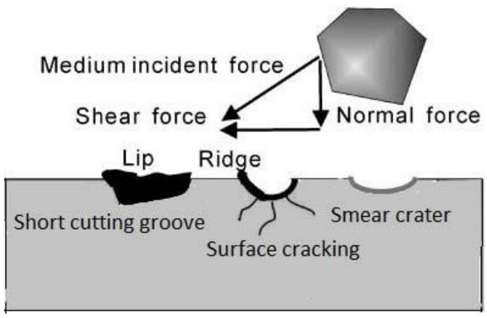

Fig. 9. Schematic mechanism of erosion at variant impingement angle.

5. Conclusion

A systematic study on the erosion resistance of high velocity oxy-fuel sprayed tungsten carbide coating has been carried out. The salient findings of the study are as follows:

- HVOF sprayed coating shows tungsten carbides are homogeneous and uniformly distributed on the surface of the substrate and a complex microstructure comprising unmelted particles.
- The erosion rate (3.2×10^2 mg/kg) is very minimum for the coating sample WC-11Co-2Cr at 30º angle of impingement compared to the erosion rate is maximum for the sample WC-8Co-2Cr at 75º angle of impingement.
- The micro-hardness (Hv 981) of WC-11Co-2Cr found to be the maximum when compared to the other two Tungsten carbide coatings-based coating compositions.
- The minimum erosion rate is observed in the coating WC-11Co-2Cr.and the maximum erosion rate was found to be for WC-8Co-2Cr at a 75º angle. The erosion resistance of WC-11Co-2Cr was the highest for the considered erosion parameters.

Abbreviations

ASTM	American society for testing of materials
HV	Hardness Value
HVOF	High Velocity Oxy-Fuel
SEM	Scanning Electron Microscope
SPE	Solid particle Erosion
XRD	X-Ray Diffraction

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