Slurry Erosion Performance of Detonation Gun Sprayed Stellite-6 on 13Cr4Ni Hydroturbine Steel at two Different Angles under Hydro-Accelerated Conditions

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Abstract— **In the current study, slurry erosion behavior of Detonation Gun (D-gun) Stellite-6 coated and uncoated 13Cr4Ni steels was observed at two different angles (30° and 90°) under a slurry concentration of 5000 ppm with erodent particle size 600 µm and rotation speed of 3800 rpm. Commercially available silica sand was used as an abrasive media. High Speed Erosion Test rig was used for experimentation. Stellite-6 coating performed better than the uncoated 13Cr4Ni steel at 30°. On the other hand, at 90°, better performance of uncoated 13Cr4Ni steel in comparison toStellite-6 coating was observed. SEM of the eroded specimens showed mixed (brittle and ductile) mode of erosion mechanism.**

Keywords— Slurry erosion, High speed erosion tester, Scan Electron Microscope, Detonation Gun component.

I. INTRODUCTION

Slurry erosion is a drastic problem faced by the components of hydroelectric power plants in all over world. This problem occurs in mainly hilly areas, especially during the rainy seasons. During the rainy season due to the increase in concentration of solid particles, filtration process is not possible [1]. Water contains Quartz, Tourmaline, Garnet, Zircon, etc of Hardness 7 on MHO scale [2]. These sediments are formed due to the fragmentation of rocks, erosion of land and land sliding because of heavy rains during the monsoon period in the Himalayan region of India [3]. Due to heavy silt content in water, the parts turbines like turbine blades, needles and nozzles get eroded and the turbine efficiency reduces and leads to high revenue loss in the hydro plant per year and such slurry wear leads to degradation of machinery performance and shortened service life [4]. Due to the impact of hard particles, erosion of underwater parts in turbines occurs which is a common phenomenon [5]. A lot of investigations have been done by the researchers to identify the factors which are responsible for the slurry erosion behavior of turbine materials due to the water containing silt. It has been shown that rougher surface can be generated due to slurry erosion at oblique angle when compared with that at normal incident. Also at oblique angles it can provide a greater susceptibility to pitting during erosion than at normal incident. Thus it is expected at oblique angles, Individual erosion events are to be more destructive than those at normal incident [6]. During erosion ductile materials are considered to loose material through a cutting and ploughing mechanism at a low impact angle [7]. On the other hand, fragmentation, cracking and removal of flakes is common phenomenon of erosion in brittle materials [8]. When a critical fracture strain is achieved at the surface then material is lost from a metal surface during erosion [9].

In order to design an erosion resistant material, consideration must be given to providing a microstructure so that the critical fracture strain never accumulates under the stress that the impacting particles impose [10]. The cast martensitic stainless steels are mainly used in the fabrication of components of the turbines and the other industrial applications which faces damages due to erosion. This is mainly due to the good mechanical properties, corrosion and erosion resistance of the steel. It is often a very difficult task to evaluate the slurry erosion performance of materials under actual service conditions; this is because of interactive effects of various parameters like slurry concentration, velocity, Particle shape and size of abrasive medium on wear rate. By increasing velocity and other operational parameters more simulated tests can be performed on materials in a laboratory test rig like real contact conditions. In the present study, the coating of Stellite-6 which has been applied on 13Cr4Ni steel using Detonation Gun and behavior of coated and uncoated steel has been observed at two different angles (30° and 90°) under a set of parameters like concentration, erodent particle size, rotation speed.

A. Detonation Spray Coating

To improve the durability and surface performance of engineering components which expose to different kind of wear such as abrasion, erosion and corrosion, thermal spray coating techniques are appearing a versatile means of developing a large variety of coatings/protective layers [11–13]. Detonation gun (D-gun) spray process is a thermal spray coating process, which provides extremely low porosity, good adhesive strength, low oxide contents, coating surface with compressive residual stresses and high intersplat strength [14, 15]. The process of D-gun spraying involves the impingement of materials in powder form through a water-cooled barrel with the supersonic speed on the surface of substrate. The two phase mixture of coating are heated to plasticity and impinges on target surface of substrate, where the high temperature, high velocity coating particles bond into the surface of substrate and a mechanical interlocking and microscopic welding may take place [16]. To resist wear ceramic materials are now usually applied in the form of coatings. The ceramic powders are having high melting point, because of which it requires a high temperature jet during coating formation, these coatings are mainly deposited by atmospheric plasma spraying [17]. However, plasma sprayed coatings produces more porous and brittle coating surface than high velocity thermal-sprayed coatings [18, 19]. But due to small porosity and close interlamellar contacts, the high-velocity spraying techniques provide greater hardness [20, 21]. This is why a number of efforts have been made to use these high-velocity spraying techniques like to spray oxides, Detonation gun spraying is mainly used [21].

II. EXPERIMENTATION

A. Substrate Material

In the present study, 13Cr4Ni stainless steels which are usually used in hydropower plants were selected. Chemical composition of 13Cr4Ni steel is given in table 1. Rectangular specimens of 10 mm X 10 mm were prepared of the steel.

B. Coating Material

Commercially available powder of Stellite-6 was deposited on CA6NM. Stellite-6 is a cobalt base alloys consist of complex carbides in an alloy matrix and Stellite is a registered Trade Name of DeloroStellite. The nominal composition (mass %) and Physical Properties of Stellite-6 is given in table 2.

C. Coating Material

Samples of 13Cr4Ni are coated with Stellite-6 using D-Gun process available with SVX Powder M Surface Engineering Pvt. Ltd., Noida, India. The standard process parameters used for depositing the coating on substrate are shown in table 3.

D. Slurry Erosion Testing

To study the slurry erosion performance of Stellite-6 coated 13Cr4Ni steel and uncoated 13Cr4Ni stainless steel specimens, a high speed erosion tester (DUCOM TR401, Bangalore make) was used which was available at BBSBEC, Fatehgarh Sahib. The tester consists of different components such as slurry tank, slurry abrasion chamber, control panel, rotor and 3 phase induction motor which are shown in Fig. 1. In slurry abrasion chamber test slurry and specimens are enclosed. When motor is started the specimens rotates. Rotational speed can be set using control panel and time can be set for a run. Slurry tank is a cylindrical stainless steel vessel, in which the required concentration of slurry is prepared. For re-circulation of slurry, three inlet pipes and three outlet pipes are provided between slurry tank and slurry abrasion chamber.

Due to rotation of rotor vacuum is created in the slurry abrasion chamber and therefore slurry from cylindrical vessel through inlet pipes to chamber and used slurry leaves the chamber and enters the tank from bottom side through outlet pipes, thus maintaining continuous re-circulation of slurry. Accelerated hydro conditions can be created by using high speed erosion tester to simulate the erosion of test specimens with slurry having abrasive particles of controlled composition and size. Main advantage of this test rig is that 12 specimens can be placed and tested at a time, thus ensuring zero tolerance to change of experimental conditions while comparing the slurry erosion performance of different specimens under similar experimental conditions. By default only cylindrical samples can be tested in this tester. Therefore placing rectangular specimen a specially designed specimen holders were attached to the rotor. The rotational radius of samples is 80 cm. These specimen holders can be set at various angles. To keep the particles uniformly suspended in the suspension, a stirrer were used in slurry tank to avoid the particles to settle down in the slurry tank.

Commercially used silica sand is used as slurry medium as silica is found to be main constituent of slurry as it is found from the literature; the slurry consists of SiO_2, Al_2O_3, CaO, and MgO in hydro power plant in northern India [5].

Slurry concentrations of average particle sizes of 600 µm were prepared to simulate the test in more accelerated conditions. Tests were carried under concentration of 5000 ppm, with erodent particle size 600 µm and rotation speed of 3800 rpm to study the slurry erosion performance of Stellite-6 coated 13Cr4Ni and 13Cr4Ni stainless steel which were placed at 2 different angles i.e. 30° and 90°. These two angles were select to analyze the performance of specimen when sand particles strike the surface tangentially and normally.

TABLE I. CHEMICAL COMPOSITION OF 13Cr4Ni STAINLESS STEEL (WT %)

Steel	C	Si	Mn	Cr	Ni	N	S	Cu	Co	P	Mo	Fe
13Cr4Ni	0.06	0.74	1.16	13.14	3.9	--	0.014	0.088	0.035	0.015	0.61	Bal.

TABLE II. NOMINAL COMPOSITION (MASS %) AND PHYSICAL PROPERTIES OF STELLITE-6

Co	Cr	W	C	Others	Hardness	Density	Melting Range
Base	27-32	4-6	0.9-1.4	Ni, Fe, Si, Mn, Mo	36-45 HRC 380-490 HV	8.44 g/cm3 0.305 lb/in3	2340-2570 °F 1285-1410 °C

TABLE III. D-GUN SPRAY PROCESS PARAMETERS

Parameters	Stellite-6 Coating
Oxygen flow rate (O_2)	3120 SLPH
Pressure	0.2 MPa
Acetylene flow rate (C_2H_2)	2400 SLPH
Pressure	0.14 MPa
Nitrogen flow rate (N_2)	1040 SLPH
Pressure	0.4 MPa
Spray angle	90°
Spray distance	150 mm
Power	450 VA

The interaction of rectangular specimen with slurry particles in slurry chamber is shown in Fig.2. A typical erosion test cycle started with mounting of specimen holder at the proper place at correct angle. Then specimen was placed in the holders in the slurry chamber. After fixing the specimens in holders every time chamber was made air tight by tightening the nuts at four places so that proper vacuum can be created. The water was filled in stainless steel water tank and silica sand of appropriate particle size was added to the water for preparing required concentration. Then rotational speed was set and test was started. After completion of slurry erosion test cycle of 1 hour, specimens were removed from the specimen holders; the specimens were cleaned with brush using acetone to remove attached sand particles from the surface of specimens. The weight of the specimens was measured before and after each slurry erosion cycle using micro weighing scale having an accuracy of 0.1 mg. The loss in mass of each specimen was recorded. As erosion is a surface phenomenon, therefore surface area of each specimen was calculated by taking the measurement of length and width at two places, taking their mean for getting average length and width of specimen with the help of digital vernier caliper of least count 0.01 mm.

For calculating specific mass loss following relation was used

$$\text{Specific mass loss} = \text{mass loss (g)} \times 10^6 / \text{Exposed surface area } (m^2)$$

The slurry erosion process was repeated for six cycles, duration of each cycle was 1 hour. The results have been plotted on cumulative mass loss per unit area in (g/m2) versus exposure time (h) plot to compare the slurry erosion behavior of substrate and coatings.

III. RESULTS AND DISCUSSION

A. *Erosion of uncoated and coated steel*

Fig. 3 shows cumulative weight loss per unit area (g/m^2) versus time (h) graph of bared 13Cr4Ni stainless steel at 30° and 90° under concentration of 5000 ppm, erodent particle size 300 μ and rotation speed of 3800 rpm. From graph it can be observed that as the time increases the cumulative weight loss per unit area increases for material at both angles. Also it can be seen that after a run

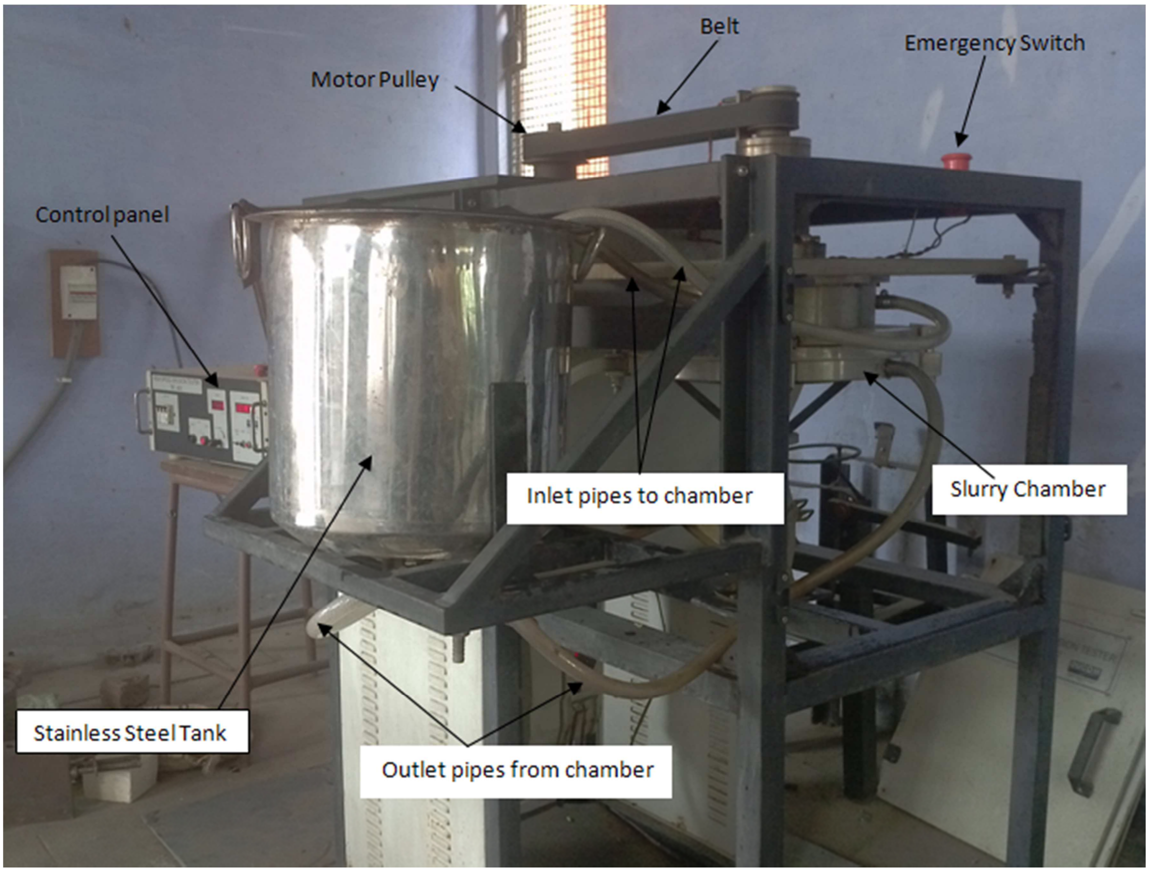

Fig. 1. Experimental setup of High Speed Erosion Tester (DUCOM TR401)

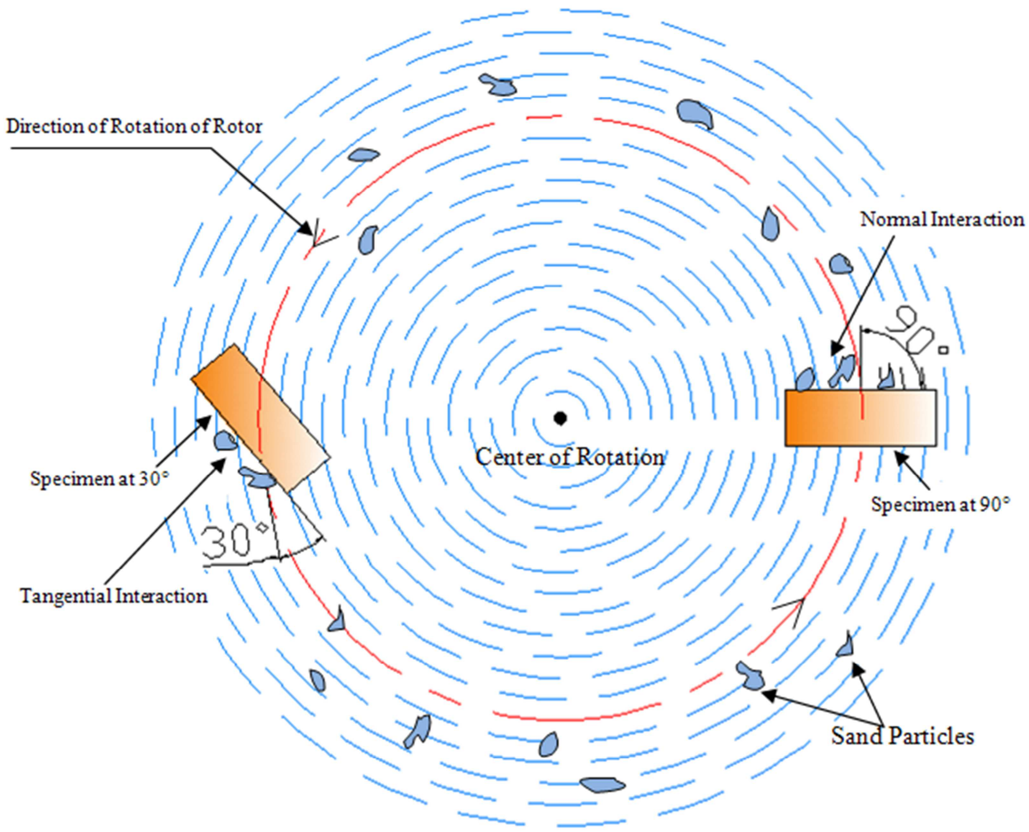

Fig. 2. Schematic diagram showing interactions of the slurry particles with rectangular specimen in slurry chamber at 30° and 90°

of 6 hours overall specific weight loss for 13Cr4Ni at 30° is 848.36 g/m^2 and 13Cr4Ni at 90° it is 151.04 g/m^2.It means specific weight loss for 13Cr4Ni at 30° is 5.6 times the specific weight loss of 13Cr4Ni at 90°.

In Fig. 4 there is a comparison between Stellite-6 at 30° and Stellite-6 at 90° on cumulative mass loss per unit area versus time graph. With the increase in time weight loss per unit area of Stellite-6 increases for both angles. After 6 hour run overall specific weight loss for Stellite-6 at 30° is 161.91 g/m^2 and for Stellite-6 at 90°coating it is 314.22 g/m^2. Specific weight loss for Stellite-6 at 90° is 1.95 times specific weight loss for Stellite-6at 30°.

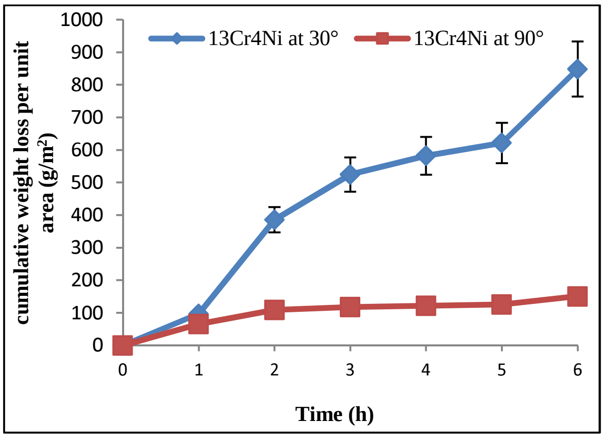

Fig. 3. Comparison between cumulative mass loss per unit area of 13Cr4Ni at 30° and 90°

Fig. 5 shows cumulative weight loss per unit area (g/m^2) versus time (h) graph of bared 13Cr4Ni stainless steel and Stellite-6 coated 13Cr4Ni at 30° under same set of parameters. It can be observed that as time progresses cumulative weight loss per unit area also increases for both. After a run of 6 hours overall specific weight loss for 13Cr4Ni is 848.36 g/m^2 and for Stellite-6 coating it is 161.19 g/m^2. It means specific weight loss for 13Cr4Ni is 5.26 times the Stellite-6.

Cumulative mass loss per unit area of 13Cr4Ni and Stellite-6 at 90° is shown in Fig. 6. From the graph it can be seen that 13Cr4Ni performed better at 90° as the

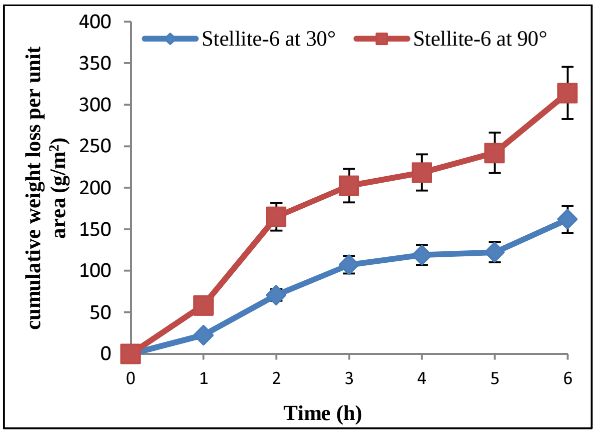

Fig.4. Comparison between cumulative mass loss per unit area of Stellite-6 at 30° and 90°

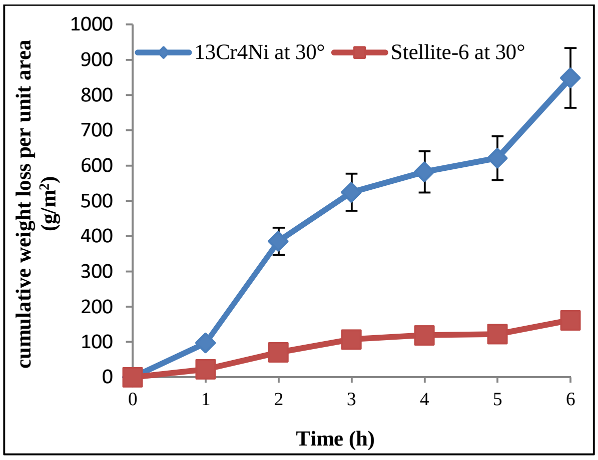

Fig. 5. Comparison between cumulative mass loss per unit area of 13Cr4Ni and Stellite-6 at 30°

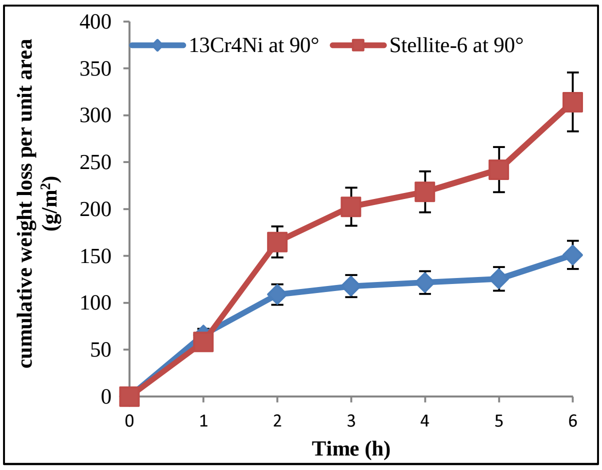

Fig. 6. Comparison between cumulative mass loss per unit area of 13Cr4Ni and Stellite-6 at 90°

maximum weight loss for 13Cr4Ni at 90° is less than the Stellite-6 at 90°. The maximum weight loss for Stellite-6 at 90° is 345.31 g/m^2 and for 13Cr4Ni at 90° it is 314.22 g/m^2.

B. *Material Removal Mechanism*

In the present study rectangular specimens were rotated in high speed tester containing the slurry particles. This slurry particles may cause abrasion and erosion damage of the specimen surfaces. In the present study the specimen was placed at two different angles i.e. 30° and 90°. When specimen is at 90° there will be only normal interaction of sand particles with surface of specimen therefore this interaction can make the material to fail by fatigue or under plastic deformation. Whereas when specimen is at 30° then sand particles will hit surface tangentially. Hitting force can be resolved into two components i.e. tangential component and perpendicular component. Tangential component is parallel to the surface of specimen which has a cutting effect at the surface. While, the perpendicular component may cause plastic deformation or it may be the reason of fatigue failure. Therefore it can be considered that slurry erosion of specimen at 90° will be due to the fatigue alone whereas at 30° it can be considered that slurry erosion of the specimens is occurring due to cutting abrasion and deforming abrasion simultaneously. To investigate the mechanism of material removal, SEM analysis of all eroded specimen were done. The SEM micrographs of eroded surfaces are shown in Figs. 7, 8, 9, 10.

In Fig. 7, SEM features of eroded surface of Stellite-6 at 30° are shown. It can be seen that pitting effect as well ploughing effect is appearing. For substrate as well as for coating at 30° the same effect can be seen from Fig. 7 and Fig. 8. Ploughing of material in the direction of flow of slurry can be observed from the same Figures. Appearance of pits confirms the fatigue failure. It can also be observed that there is also some removal of grains from the surface. Therefore relevant mechanism for erosion is mixed i.e. brittle as well as ductile.

Fig. 9 and 10 show the SEM analysis of Stellite-6 at 90° and 13Cr4Ni at 90° respectively. As the slurry particles interacted with the surfaces normally therefore only pits are there. It shows that material is mainly removed due to fatigue and brittle failure.

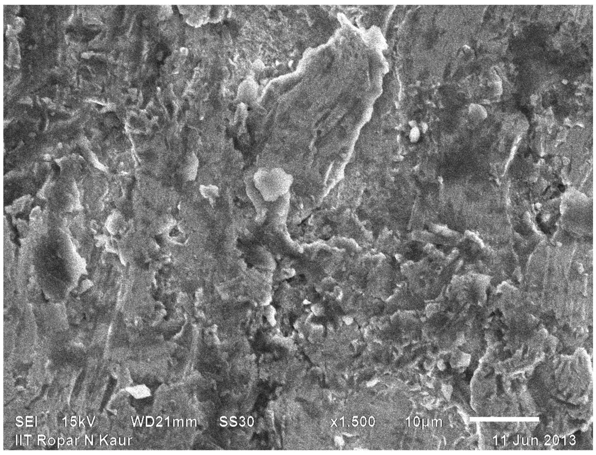

Fig. 7. SEM features of eroded surface of Stellite-6 at 30°

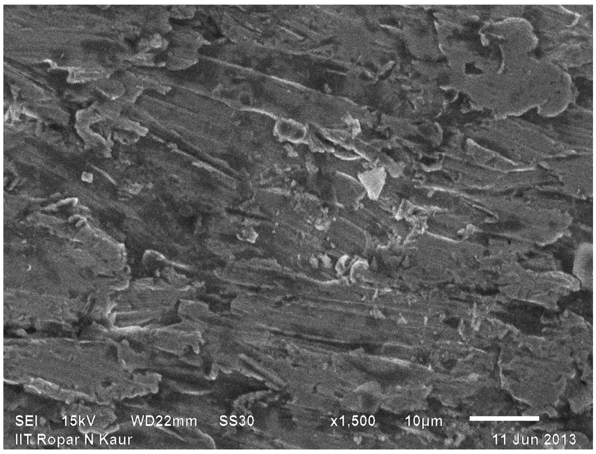

Fig. 8. SEM features of eroded surface of 13Cr4Ni at 30°

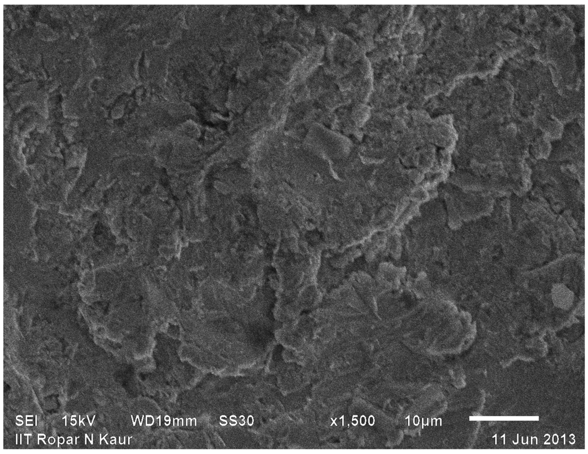

Fig. 9. SEM features of eroded surface of Stellite-6 at 90°

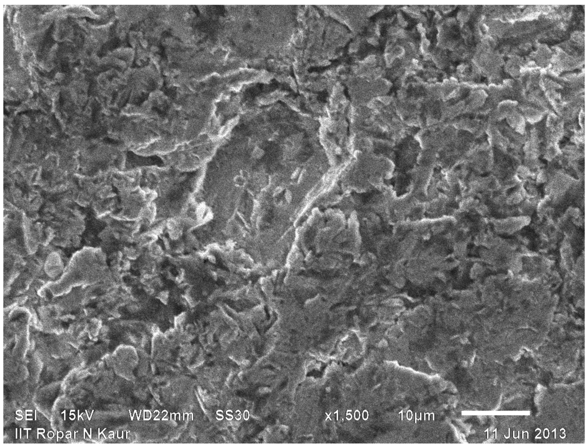

Fig. 10. SEM features of eroded surface of 13Cr4Ni at 90°

IV. CONCLUSIONS

The following conclusions may be drawn depending on the results obtained from this study:

a) Due to ductile nature, 13Cr4Ni steel performed better at 90° in comparison to at 30°. On the other hand, Stellite-6 showed better resistance to slurry erosion at 30° in comparison to at 90°.

b) Due to higher hardness, Stellite-6 coating performed better at 30° than uncoated 13Cr4Ni.

c) Substrate 13Cr4Ni steel (due to high toughness) showed better slurry resistance than Stellite-6 coating at 90°.

d) It was found that fatigue and brittle failure was dominating material removal mechanisms for the coated and uncoated steels at 90° whereas at 30°, ploughing mechanism was dominated.

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