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Performance evaluation of hard faced turbine steel under slurry erosion conditions

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Abstract
Erosion wear at the wetted passages is a critical parameter for selection and design of slurry transportation systems. Erosion wear is a complex phenomenon and is difficult to predict for multi-sized particulate slurries mostly due to representation of its dependence on a single particle size. In the present work, an effort has been made to develop a methodology to determine the nominal particle size of multi-sized particulate slurry for estimation of mass loss due to the erosion wear. It is seen that a particle size representing the mass average of the particles can be taken as the nominal size. The effect of presence of fine particles (<75 μm) in relatively coarse particulate slurry has also been studied separately by conducting experiments in a pot tester. It is observed that a reduction of approximately 40–50% in the wear is possible by addition of finer particles 25% (w/w) of bigger particles.

1. Introduction
Erosion wear is probably the most significant cause of mechanical damage of equipment components coming in contact with erosive bodies [1, 2]. Erosion wear is a process of progressive removal of material from a target surface due to repeated impacts of solid particles. The particles suspended in the flow of solid-liquid mixture erode the wetted passages limiting the service life of equipment used for slurry transportation systems [3]. Slurry erosion of turbine components is a very serious problem in most of hydro power plants all around the world especially in Himalayan region of India [4]. The erosion occurs in agriculture sector also, the impellers of the centrifugal pumps damaged due to the impact of erodent particles entrained in water [5]. Many researchers have tried to improve the surface of the material or the components of machinery that deals with such situations, but due to its dependency upon many causes and factors, it is difficult to find out the common cause. **Steward et al [5]** studied the erosion wear of different pipe materials used for slurry transportation. A closed loop pipeline rig was used with jet impact to find the effect of erosion wear on different pipeline materials. They tested three types of materials which were: (1) Steels (2) Elastomers (3) Polymers. The material tested were high density polyethene, polyvinyl chloride, Polyurethane with different hardness rubber, basalt. Gold tailings and crushed gold quartz were used as slurry. A ranking in the wear resistance of pipeline materials for the transportation of solids was made, even though the wear rates differ according to solids transported and the transport parameters. **Wang et al [6]** studied the erosive wear in an alkaline slurry containing alumina particles of mild steel BS 6323 (Fe-C), the AISI 410 stainless steel (Fe-Cr-C), and the AISI 304 stainless steel (Fe-Cr-Ni), was carried out, by means of rotating cylinder, three-electrode erosion corrosion test, with a view to investigation into the roles of the typical elements and the mechanical and chemical properties in the erosive wear under simultaneous controlled corrosion. The total weight loss of erosion-corrosion was obtained. The result was compared and interpreted, for each material, by a full microscopically examination of the erosion-corrosion scars using scanning electron microscopy (SEM). It was found that the overall performance under erosion corrosion in a descending order was the stainless steels AISI 304, AISI 410, and the mild steel. The individual contribution of each erosion and corrosion process was thus further separated through corrosion charge conversion using the Faraday's second law and the results were interpreted by discussion, on basis of the experimental and microscopically evidences, of the main factors that influenced the mechanical and wear behavior, in conjunction with those influencing corrosion and passivity. **Grewal et al [1]** proposed a parameter to predict the mechanism of erosion in materials named as "erosion mechanism identifier" ζ Suitability of ζ in predicting erosion

mechanism of ductile and brittle materials was evaluated using the data reported in the literature. It was observed that ζ is able to predict the erosion mechanism for both categories of materials. The predictability of ζ was not restrained by different operating conditions. This new parameter addressed the limitations of the older one and facilitated the erosion mechanism prediction at different operating conditions. A linear correlation between the brittleness and ζ was also observed. It is indicated that the tendency of material to exhibit brittle erosion mechanism increases with increase in brittleness. **Clark et al [7]** studied the slurry erosion performance of 11 commercially available wear resistant plate and pipeline steels. The hardness of the material surface was chosen up to 750VHN. A carioles tester was used for experimental analysis. The tester was operated at 5000rpm, slurry concentration of 10% wt and particle size of 200-300μm silica sand slurry. It was concluded that hardened steel showed more erosion resistance than non-hardened, carbon steel line pipe material. **Moore et al [8]** conducted experimental work to evaluate the performance of thermal spray coatings as corrosion barriers when applied to interior pipe walls. The ability to apply these coatings has recently been developed. They attempted to validate the suitability of these coatings with aggressive geothermal fluids, as well as identify the procedures necessary to assure a successful coating application. It was anticipated that a coated steel pipe will replace the cement lined or nickel alloy piping currently used.**Goyal et al [2]** deposited WC-10Co-4Cr and Al2O3+TiO2 coatings on the turbine material CF8M by High velocity oxy fuel process. High speed slurry erosion test rig was used. Three parameters namely average particle size, speed (rpm), and slurry erosion were studied. The bare and Al2O3+TiO2 coatings showed ductile and brittle mechanisms during slurry erosion tests. On the other hand, WC-10Co-4Cr showed mixed behavior (mainly ductile). The rotational speed was found to be most dominating factor in slurry erosion testing. The effect of average particle is more dominating in the case of Al2O3+TiO2 as compared to WC-10Co-4Cr and uncoated CF8M steel. **Chauhan et al [3]** have done the comparative study of stainless steel (termed as 13/4) and nitronic steel (termed as 21-4-N) used in hydroelectric projects on the basis of erosion behavior by means of solid particle impingement using gas jet. The eroded surfaces after erosion tests were analyzed by scanning electronic microscopy. It was observed that the 21-4-N nitronic steel possesses better resistance to erosion in comparison to 13/4 stainless steel. The austenitic matrix of the nitronic steel possesses high hardness, high tensile toughness and work hardening ability, which results in higher erosion resistance. **Mbabazi et al** [**9**] investigated the effect of ash particle impact velocity and impact angle on the erosive wear of mild-steel surfaces through experiments. The experimental data were used to calibrate a fundamentally-derived model for the prediction of erosion rates. This model incorporates the properties and motion of the ash particles as well as target metal surface properties. **Machio et al [10]** studied the erosion wear of WC-12Co, WC-17CO and experimental WC-10VC-12Co and WC-10VC-17Co coatings. The coatings were deposited on stainless steels substrates using a high velocity oxy-fuel (HVOF) thermal spray process. The slurry used was silica sand in water. It was concluded that WC-VC-Co coatings exhibit higher erosion resistance then commercial WC-Co coatings. In slurry erosion, the best performance of the VC-containing coatings is as good as that of the commercial WC-Co coatings. They found that erosion resistance of the WC-VC-Co coatings was similar to that of the commercial grades. This may be due to the V W C grains being less resistant to impact fracture because of high hardness. They also found that coatings with higher cobalt content showed higher wear rate.

It is clear from the literature review that slurry erosion of turbine steel is a severe problem. Due to this problem hydro power plant regularly face shut down. Many turbine researchers in recent pass have tried to increase slurry erosion resistance of the steel. Researchers have used various types of thermal spray coatings on the turbine steel. Literatures also reveal that AISI 316L material is mostly used for manufacturing blades of turbine, impellors of centrifugal pumps etc. A few researchers have tried to improve the corrosion resistance of this steel by using thermal spray coating. The erosion resistance of this steel AISI 316L can also be increased by hard facing of this material. Therefore in the present research work it was decided to study the effect of various parameters on the slurry erosion of hard faced AISI 316L material. The material used for the experiment was AISI316L steel. This was purchased from a scrap dealer of tractor market in Patiala. The chemical composition was confirmed using spectroscopy analysis at Munjal Castings Pvt. Ltd. Ludhiana, It was in the form of rectangular flat bar of the dimensions 60mmx20mmx6mm.

2. Material and Methods

2.1. Material

The subject material for the research i.e. AISI 316L steel was purchased from a scrap dealer of tractor market in Patiala. This material is usually regarded as the standard "marine grade stainless steel". This material is used to manufacture the impellers of centrifugal pumps used in agricultural sector. The austenitic structure also gives these grades excellent toughness. Spectroscopy analysis preformed at Manjal Pvt. Ltd. Ludhiana to ensure the chemical composition of the material. The mechanical properties of AISI 316 L steel are shown in Table 1

Table1: Mechanical Properties

Tensile Strength (MPa) min	485
Yield Strength (MPa) min	170
Brinell Hardness (HB) max	217

2.2. Surface improvement by hard facing technique

The base material i.e. AISI316L steel was Hard Faced with Cobalt based and Titanium based electrodes. The welding was accomplished with SMAW process. The nominal composition of cobalt based and titanium based electrodes are given in the next chapter. The parameters take during the welding process are presented in the Table 2.

Table 2: Welding Parameters

Welding Process	**SMAW**
Preheat Temperature(^{0}C)	150
Inter-pass Temperature(^{0}C)	150-200
Welding Current (A)	90-120

2.3. Preparation of samples

The Hard Faced material was machined to obtain specimen of dimension 40x18x6 mm as shown in figure 1 according to the sample holder of the slurry erosion test rig. Then the specimens were grinded with the help of surface grinder to obtain surface finish. Then the various samples were grinded with the help of surface finish. Then the various samples were prepared for micro hardness test using emery paper of different grit sizes.

(a) **(b)** **(c)**

Figure 1: Prepared Samples (a) Bare, (b) HF Alloy1, (c) HF Alloy2

2.4. Description of slurry erosion test rig

The rig was fabricated at Department of Mechanical engineering, Punjabi University Patiala. The test rig shown in figure 2 consists of a centrifugal pump, conical tank, nozzle, specimen holder, valves and flow meter. Centrifugal pump driven by 5 HP, 1500 rpm electric motor has a capacity of max pressure 13.5 bar at a discharge of 240 l/min. During test the temperature of slurry increase to a certain level and thereafter remains constant, which is due to mechanical action of pump. The flow rate of the slurry is controlled with help of main valve and bypass regulator valve between delivery side and nozzle. The nozzles are detachable, so we attach as desired nozzle size. The rectangular tapered tank having 600x450 mm at top which converges to 100x100 mm at bottom through a length of 120mm was used to store the slurry. A mesh is struck inside the pipeline. Slurry flowing through the pump at high pressure is converted into high velocity stream while passing through the converging section of the nozzle diameters of 3 mm and 5 mm. The standoff distance between the nozzle and specimen was 25 mm. After shrinking the specimen slurry falls back into the tank, a holder is located on the top of tank enclosed in a casing made of steel of avoid the splashing of slurry. The major parts of jet erosion tester are given below:

- Electric motor
- Centrifugal pump
- Slurry tank

- Pressure gauge
- Flow control valves
- Nozzle and Holder assembly
- Drainage valve

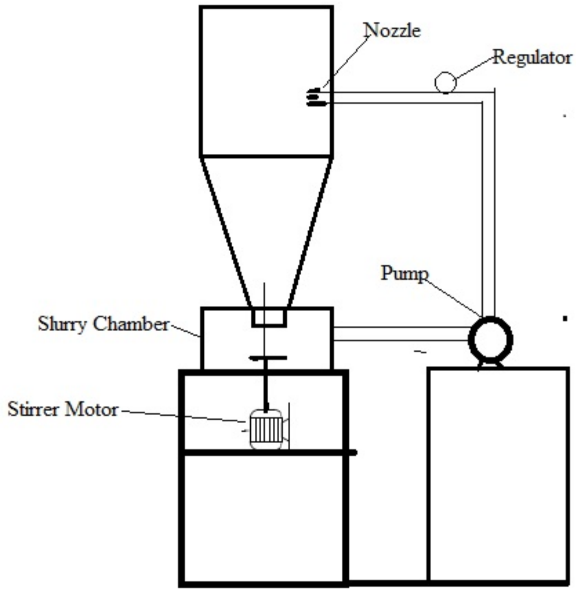

Figure 2: Schematic diagram of Test Rig [2, 4]

In jet erosion a high velocity jet strikes upon the surface of the specimen that is fixed in front of the nozzle. The jet is consists of water and sand of various particle sizes. The slurry is also made of different concentration of the sand in the water. The amount of material removed is determined by the weight loss. The slurry is re-circulated in the test rig. For size distribution of sand particles used in slurry preparation sieve analysis is carried out at Geo Tech lab of civil department in Punjabi University Patiala. The BSA number of sieve analysis is 150,350,475,600 which are selected.

2.5. Experimental Design

The adopted experimental design was factorial design. For scenario with a small number of parameters and level (1-3) and where each variable contributes significantly, factorial design can work well to determine the specific interactions between variable. The different level of particle sizes, level of concentration and different sizes of nozzles diameter used are given in the tables 3, 4 and 5 respectively.

Table 3: Particle Size

Particle Size	In µm
G1	300
G2	600

Table 4: Concentration

Particle Size	In ppm
C1	40,000
C2	60,000

Table 5: Nozzle Diameter

Nozzle Size	In mm
N1	3
N2	5

Table 6 shows the nomenclature of the specimens:

Table 6: Nomenclature

Specimen	Nomenclature					
Bare	A1	A2	A3	A4	A5	A6
HF Alloy 1	A11	A22	A33	A44	A55	A66
HF Alloy 2	A111	A222	A333	A444	A555	A666

Hence according to the factorial design of experiments, total 18 experiments were performed. The factorial design of experimentation is shown in table 7.

Table 7: Factorial Design

RUN NO.	SPECIMEN OF BARE	SPECIMEN OF HF ALLOY 1	SPECIMEN OF HF ALLOY 2
1	A1G1C1N1	A11G1C1N1	A111G1C1N1
2	A2G2C2N2	A22G2C2N2	A222G2C2N2
3	A3G1C1N1	A33G1C1N1	A333G1C1N1
4	A4G2C2N2	A44G2C2N2	A444G2C2N2
5	A5G1C1N1	A55G1C1N1	A555G1C1N1
6	A6G2C2N2	A66G2C2N2	A666G2C2N2

3. Results and discussion

3.1 *Slurry erosion behavior of the bare aisi 316l steel and hard faced with cobalt based and titanium based and titanium based electrodes*

The AISI 316L steel is used as impeller material in the centrifugal pumps used in the agriculture sector. Although it is quite resistance of slurry erosion and the cavitations' erosion, but to make it more resistant to such erosion, hard facing of the surface is done with cobalt based and titanium based electrodes. In this section the performance of bare specimens is considered. The specimens hard faced with alloy 2 i.e. titanium based electrodes shows better performance than the bare and hard faced with alloy 1 i.e. cobalt based. The alloy 2 shows slightly better performance than the alloy 1 in the all 6 runs but overall performance of alloy 1 is better than the bare. All three specimens were experimented with the different variables like average particle size in the slurry, different concentration and different diameters size of the nozzles at velocity 40m/s and angle of impingement 90°. The mass loss in mg/cm^2 with respect to time for all the six runs is shown in the figure 4.1 to 4.6. Maximum erosion for bare specimen and hard faced with alloy 1 takes place at run 4 and minimum erosion takes place at run 1 run 2. Maximum erosion of alloy 2 takes place at run 4 and minimum at run 1, run 2 run 5 and run 6. Following are the slurry erosion behavior of the subject material AISI 316L steel and hard faced with cobalt and titanium based electrodes at various runs:

Run 1:

The Run 1 was conducted by keeping all the parameters at first level according to factorial design of experiments. This run was performed at particles size of 300 um, 40,000 ppm concentration and nozzles diameter of 3 mm with velocity of 40 m/s and angle of impact 90°. Table 8 shows mass loss in mg/cm² with respect to time interval of different samples.

Table 8: Mass loss in mg/cm^2 during Run 1

Specimen Type	0 min	20 min	40 min	60 min
Bare	0	4.12	8.42	13.7
HF Alloy 1	0	3.53	7.35	12.21
HF Alloy 2	0	2.43	7.58	12.33

The plot showed in the figure 3 compares the erosion behavior of bare material and both type of hard specimens (HF Alloy1 and HF Alloy 2). As shown in the plot the erosion is less for first 20 minutes and increasing as time increases. This may be due the formation of cavity. Both hard facing alloys shows the slight difference in their performance. Erosion rate is less in this run may be due to having the first level of parameters.

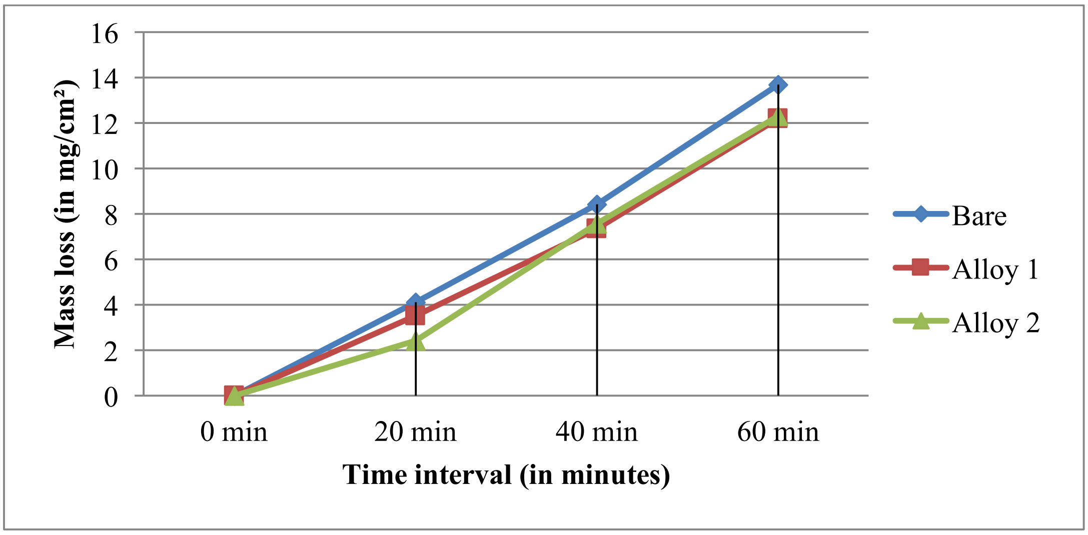

Figure 3: Comparison of Mass Loss (Run 1)

Run 2:

The run was conducted keeping the parameters according to factorial design of experiments. This run shows almost equal results for all three types of specimens. This run was performed at particles size 600 um, concentration of the slurry 40,000 ppm and nozzle diameter of 3 mm. The velocity during the experiment was 40 m/s and angle of impingement 90°. The plot as shown in the figure 4 depicts that as in the Run 1, the hard faced alloys shows slightly better performance than the bare specimen. Both hard faced alloys shows almost equal performance for equal level of parameters in this Run. Firstly the erosion rate was less but then it increases as the time increases.

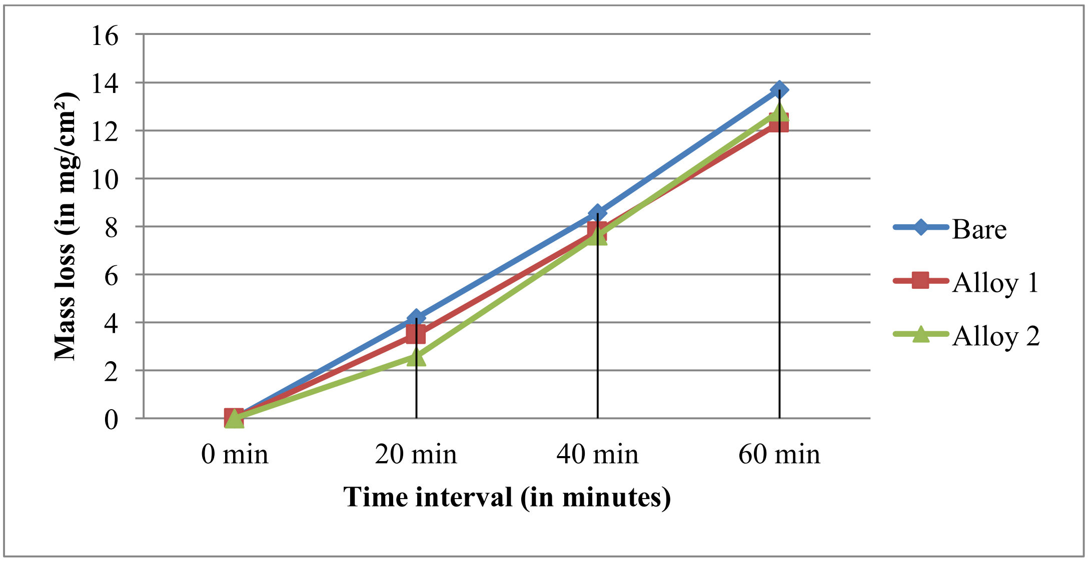

Figure 4: Comparison of Mass Loss (Run 2)

Run 3:

The Run 3 was conducted by keeping parameters according to factorial design of experiments. The particles size was 300 um, concentration was 60000 ppm and nozzle diameter was 3 mm. The experiment was performed at volecityof40m/s and having angle of impingement 90°. The plot shown in the figure 5 shows the erosion rate is increasing as the time of the experiment is increasing. In this run, both hard faced alloys shows better performance than the bare specimen. There are different results between hard faced alloys after the 20 minutes and after 40 minutes of experiment, but ultimately both shows equal erosion after completion of the experiment of 60 minute

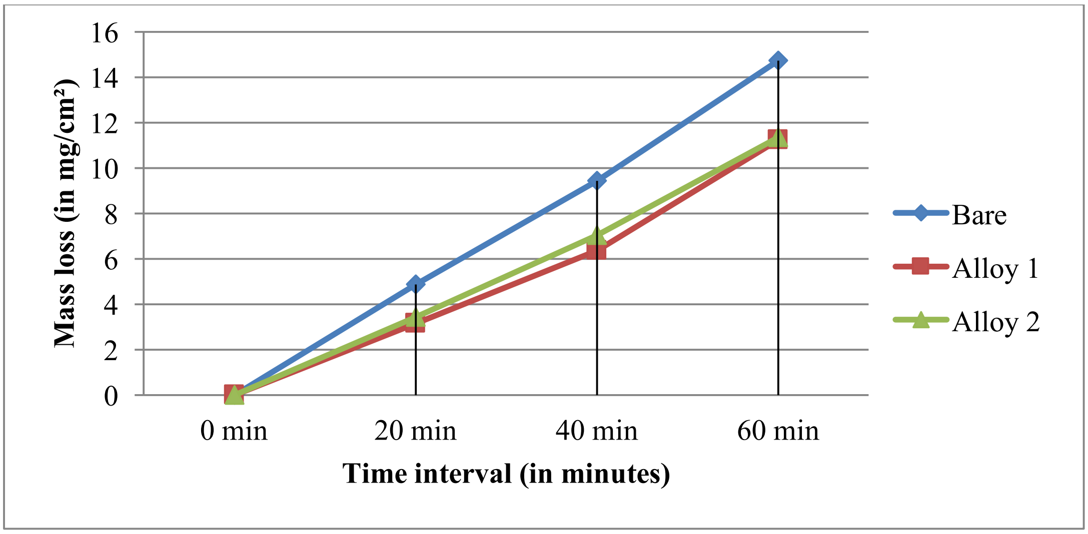

Figure 5: Comparison of Mass Loss (Run 3)

Run 4:

The Run 4 was conducted by keeping parameters according to factorial design of experiments. The particles size was 600 um, concentration of the slurry was 60000 ppm and nozzle diameter was 3 mm. The experiment was performed at velocity of 40 m/s and having angle of impingement 90°.

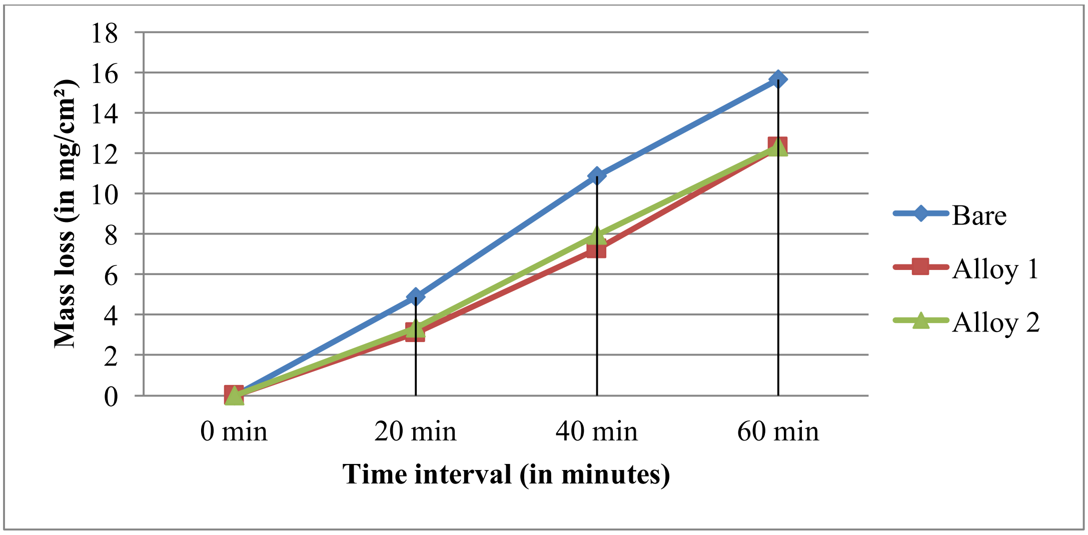

Figure 6: Comparison of Mass Loss (Run 4)

The plot shown in the figure 6 shows that erosion rate is quite high at second level of all three samples. But at the end hard faced alloys shows better result as compare to bare material.

Run 5:

The Run 5 was conducted by keeping parameters according to factorial design of experiments. The particles size was 300 um, concentration of the slurry was 40,000 ppm and nozzle diameter was 5 mm. The experiment was performed at velocity of 40 m/s and having angle of impingement 90°.

The plot drew in the figure 7 shows that there is less erosion in all the samples up to 20 minutes. Erosion rate is quite high at second level of all three samples. But at the end hard faced alloys shows better result as compare to bare material.

Run 6:

The Run 6 was conducted by keeping parameters according to factorial design of experiment. The particles size was 600 um, concentration of the slurry was 60000 ppm and nozzle diameter was 5 mm. The experiment was performed at velocity of 40 m/s and having angle of impingement 90°. The plot drew in the figure 8 shows that there is high erosion in all the samples after 40 minutes. Erosion rate is increasing with respect to time in all the samples. . But at the end hard faced alloys HF Alloy 2 shows better result as compare to other.

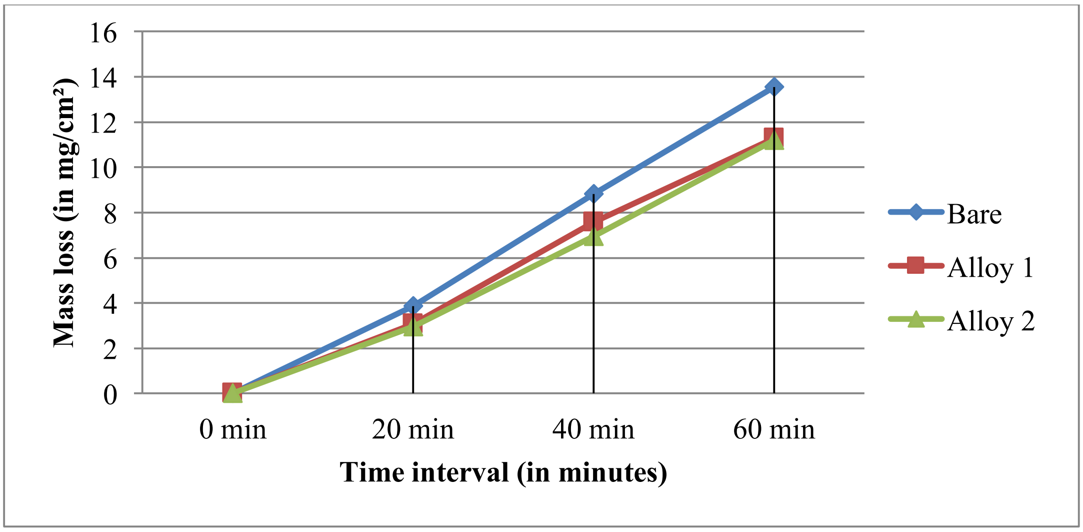

Figure 7: Comparison of Mass Loss (Run 5)

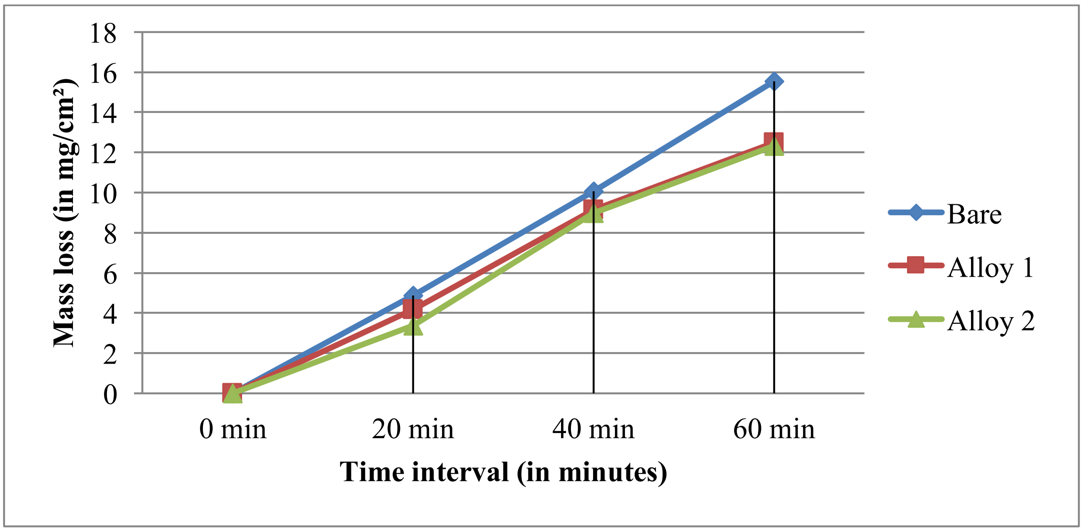

Figure 8: Comparison of Mass Loss (Run 6)

3.2 *Comparison of erosion performance at various runs for bare specimen and hard Faced alloy 1 and Hard Faced Alloy 2*

The plots, as shown in the figures 9, 10 and 11 depict the comparison of mass loss of bare material specimens and the hard faced specimens with hard alloys.

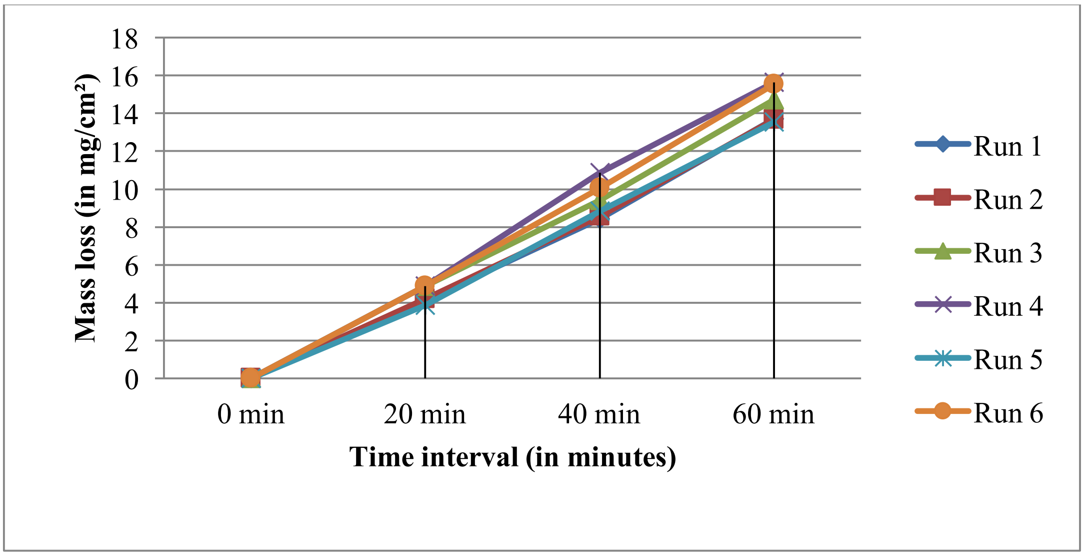

Figure 9: Comparison of Bare material various runs

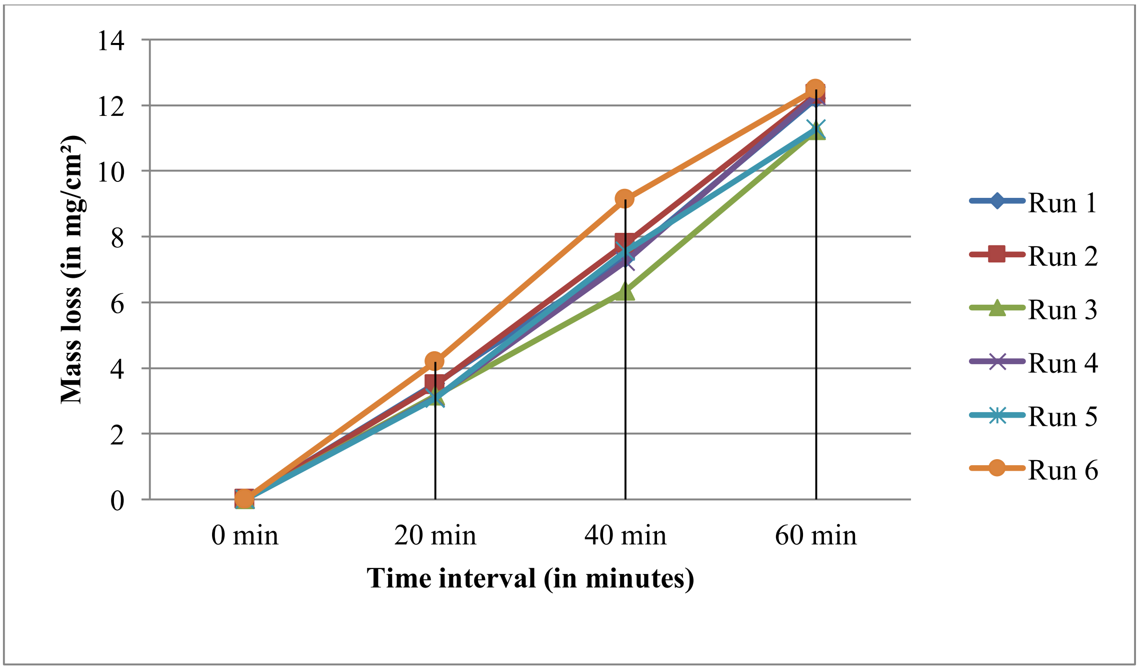

Figure 10: Comparison of HF Alloy 1 material various runs

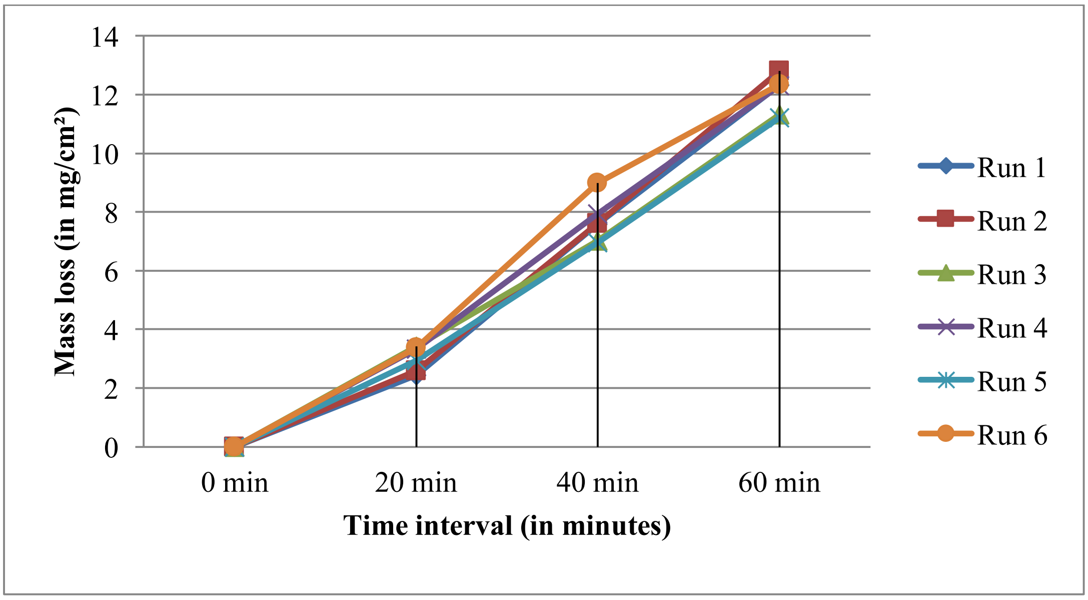

Figure 11: Comparison of HF Alloy 2material various runs

It is clearly seen that the erosion is minimum for the run 1 and 2 and maximum erosion takes place during the run 4 and run 6 for all types of specimens. The figure 9 for bare material specimens shows that there is maximum erosion for run 4 and run 6 while minimum erosion for run 1 and run 2. There is less erosion for first 20 minutes and then abruptly change in the erosion rate. The specimens with hard facing alloy 2 shown less erosion at the end of the experiment in all runs than the other two.

3.3 Comparison of Cumulative Erosion Behavior of Bare Material Specimen and the Specimen Hard Faced with Hard Alloy 1 and Hard Alloy 2

The plot shown in the figure 12 illustrates the comparison of cumulative mass loss (mg/cm^2) at various runs for bare material and hard faced material with hard faced material with hard facing alloy1 and alloy 2. The maximum erosion takes place for bare material specimens and minimum erosion is for hard facing alloy 2. This may be due to more hardness of the hardness of the hard facing alloy 2, There is maximum erosion for all the three types of specimens at run 4 and at run 6 and minimum erosion at run 1 and run 2. The problem of hard facing alloy 2 is best among all of the three types of samples.

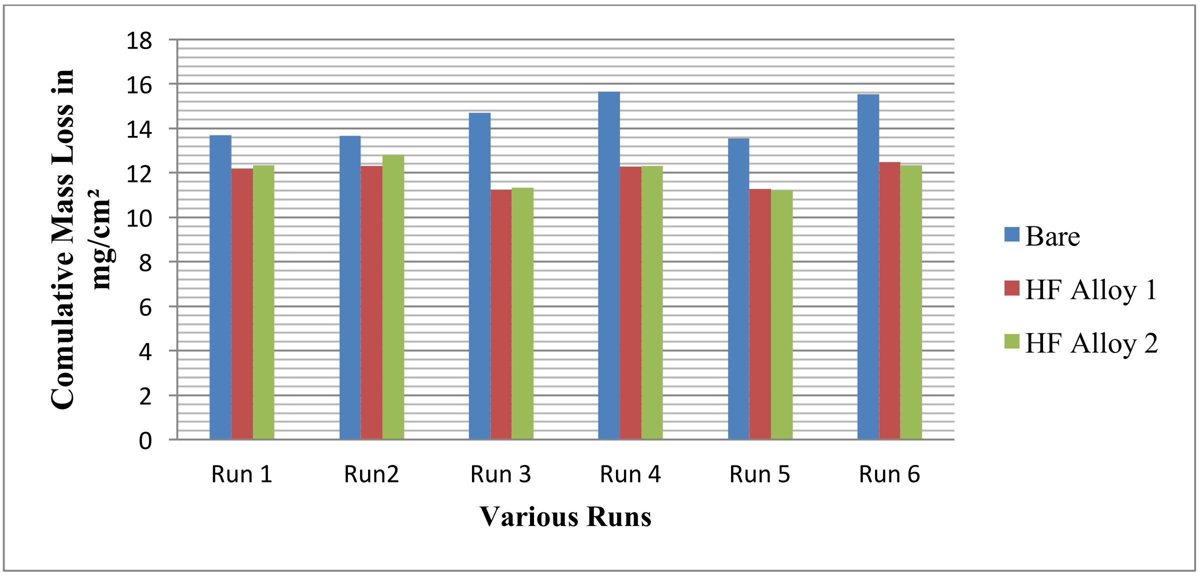

Figure 12: Comparison of cumulative mass loss of different specimens

The plot shown in Figure 12 illustrates the comparison of cumulative mass loss of different specimens of bare material and hard faced alloy after 60minute run. The maximum erosion takes place in bare material as compare to hard faced alloys. The minimum erosion is in hard faced alloy 2 in the last run.

3.4 *SEM analysis*

A scanning electron microscope (SEM) is a type of electron microscope that images a sample by scanning it with a high-energy beam of electrons. The electrons interact with the atoms that make up the sample producing signals that contain information about the sample's surface topography composition. Experimentation was examined at the Sophisticated Instrument Centre, Punjabi University, Patiala with help of scanning electron microscope to visualize change in microstructure in order to know the mechanisms which might be responsible for slurry erosion of samples in the present work, the eroded samples were analyzed under SEM. The samples selected for SEM analysis was highest eroded and lowest eroded. Figure 13 shows SEM of highest eroded bare specimen of AISI 316L steel the micrograph shows formation of micro cracks and pits on the surface of the material formed due to the erosion of material by slurry [6, 11-13]. Figure 14 shows SEM of lowest eroded bare specimen of AISI 316L steel the micrograph shows micro cracks and formation of pores on the surface of the material formed due to the erosion of material by slurry [2,8].

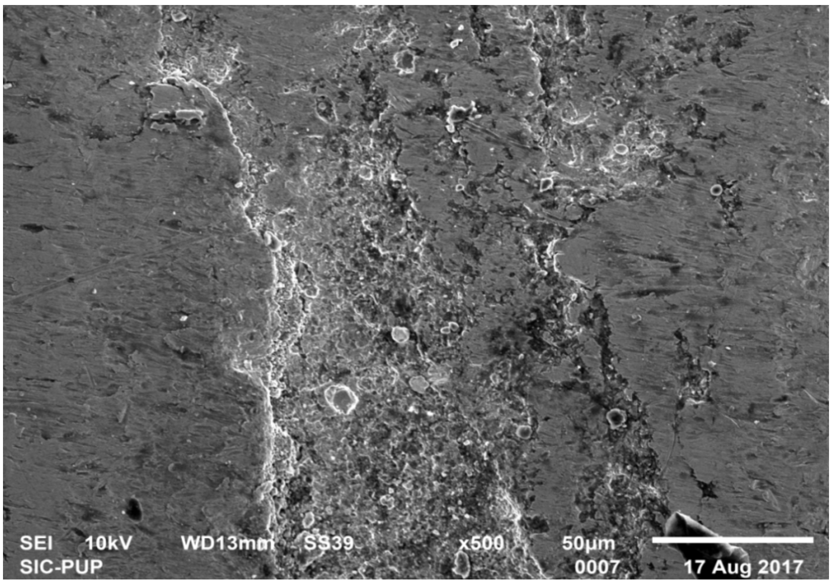

Figure 13: Highest eroded bare specimen

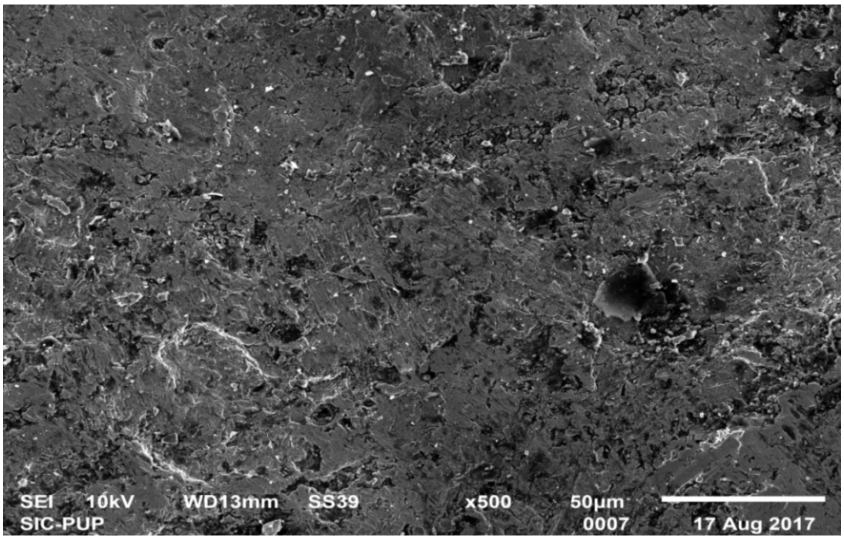

Figure 14: Lowest eroded bare specimen

Figure 15 shows SEM of highest eroded Hard Faced Alloy-1 specimen of AISI 316L steel. The micrograph shows the micro chipping due to the eroding action of the slurry. Figure 16 shows SEM of lowest eroded Hard Faced Alloy-1 specimen of AISI 316L steel. The micrograph shows the micro chipping due to the eroding action of the slurry [6, 14].

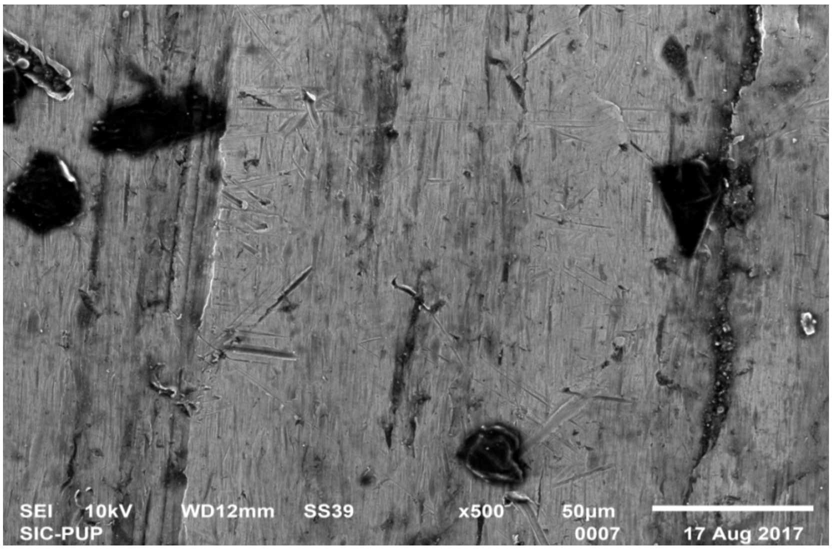

Figure 15: Highest eroded Hard Faced Alloy-1 specimen

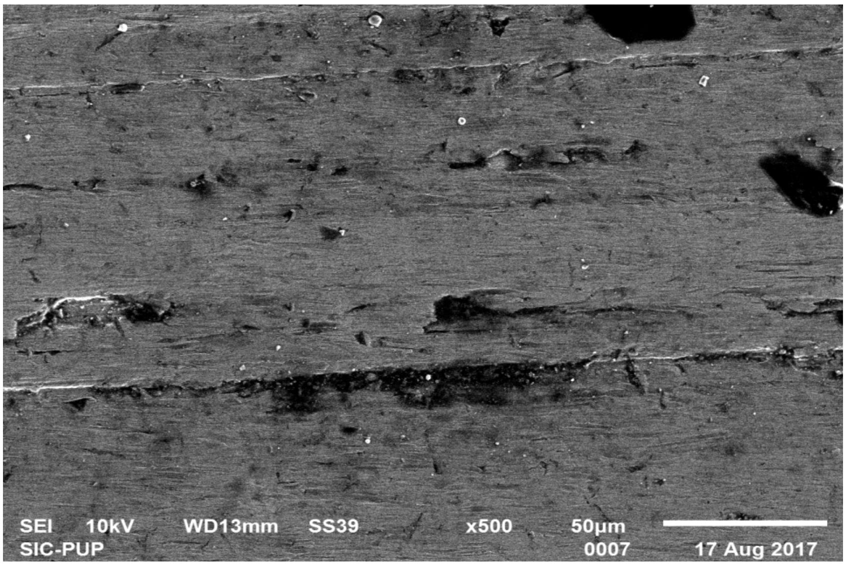

Figure 16: Lowest eroded Hard Faced Alloy-1 specimen

Figure 17 shows SEM of lowest eroded Hard Faced Alloy-2 specimen of AISI 316L steel. The micrograph shows the micro chipping due to the eroding action of the slurry. Figure 18 shows SEM of lowest eroded Hard Faced Alloy-2 specimen of AISI 316L steel. The micrograph shows the micro chipping due to the eroding action of the slurry.

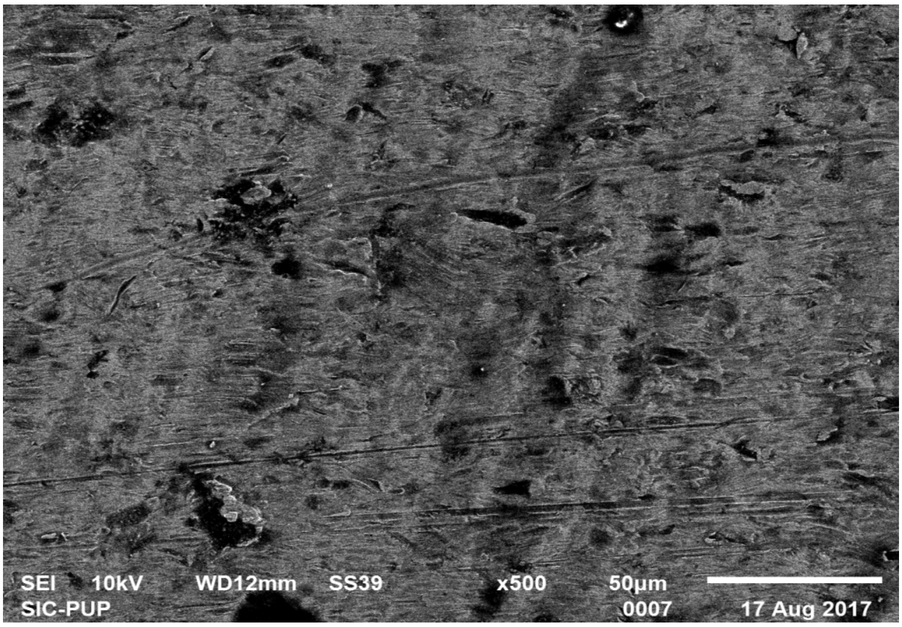

Figure 17: Highest eroded Hard Faced Alloy-2 specimen

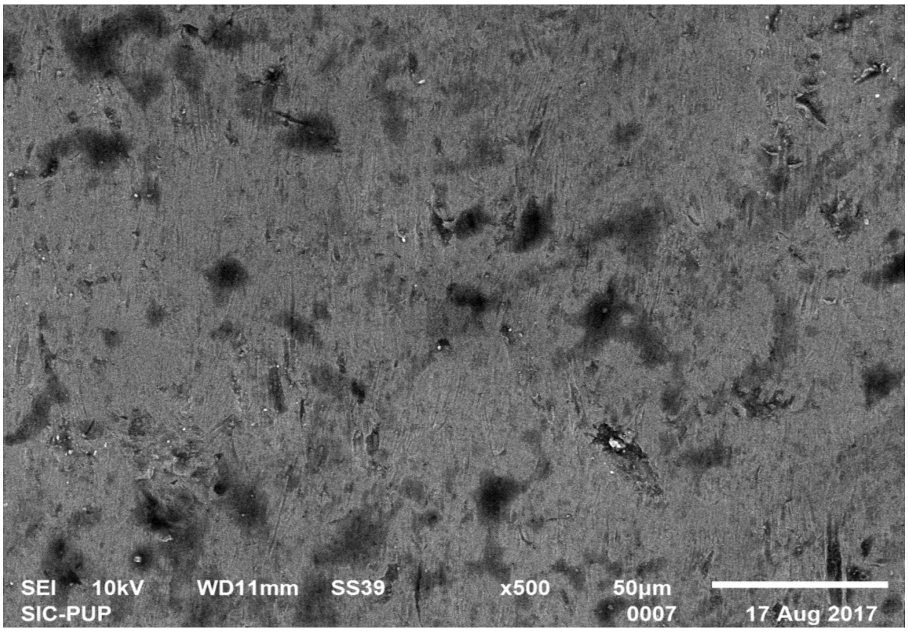

Figure 18: Lowest eroded Hard Faced Alloy-2 specimen

4. Conclusion

The selected material i.e. AISI 316L steel is most commonly used to manufacture the impellers of centrifugal pumps and used to manufacture turbine components. We selected this material with an aim to find the best substrate material having high erosion resistance. The substrate material was hard faced with cobalt based and titanium based welding electrodes. The slurry erosion tests were conducted at high velocity jet type test rig using sand of different particle sizes, different level of slurry concentration, and having different size of nozzle diameter of the jet. The erosion wear rates are evaluated in term of weight loss of material using jet erosion tester. The conclusions made from experimentation result are listed below:-

- The comparison of mass loss (in mg/cm^2) shows that erosion rate of AISI 316L steel is more than that of hard faced steel samples.
- The hard faced sample shows better performance than the bare steel in all experimental conditions.

- The maximum erosion takes place at average particle size of 600 um, level of concentration is 60,000 ppm, size of nozzle diameter 3mm, angle of impingement is 90° and velocity of 40m/d.\
- The sample hard faced with titanium based alloy is harder than hard faced with cobalt based alloy.
- The minimum erosion takes place average particle size of 300 um, level of concentration is 40,000 ppm, size of nozzle diameter 3 mm, impact angle of 90° and velocity of 40 m/s.
- The erosion of the bare steel under normal impact is due to wear mechanism and micro cutting, but for hard faced samples under similar condition is due to crack formation and deep creators.
- The sand particles are irregular in shape with sharp edges which are responsible for erosion.
- The size of nozzle diameter has no significant effect upon the erosion rate.
- In all the cases, increasing concentration will increases the erosion rate in uniform manner.
- For hard facing applied on the base materials the erosion is mainly effected by level of concentration, velocity and in the last due to average particle size.
- The particle size has significant effect on the erosion of bare and hard faced materials.
- AISI 316L steel hard faced with titanium based alloy was having better erosion resistance than that of AISI 316L steel hard faced with cobalt based alloy.

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