

INVESTIGATION ON SLURRY EROSION OF DIFFERENT PUMPING MATERIALS AND COATINGS

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DOCTOR OF PHILOSOPHY

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CERTIFICATE

This is to certify that the work presented in dissertation entitled “**Investigation on slurry erosion of different pumping materials and coatings**” is submitted in partial fulfillment of the requirements for the award of degree of **Doctor of Philosophy** under the supervision of **Dr. Satish Kumar**, (Associate Professor, Mechanical Engineering Department, National Institute of Technology, Jamshedpur, India) and **Prof. S. K. Mohapatra** (Senior Professor and Former Head, Mechanical Engineering Department, Thapar Institute of Engineering and Technology, Patiala). The contents of this thesis, in full or in parts, have not been submitted to any other Institute or University for the award of any degree or diploma.

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(Slurry erosion Lab, Mechanical Engineering Department, Thapar Institute of Engineering and Technology, Patiala)

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ABSTRACT

Centrifugal slurry pumps are widely used for transportation of solids through pipeline in many chemical and mining industries. Erosion wear considered as one of the important parameters which plays significant role in slurry transportation system by affecting both initial cost and life of its components. In the present work, erosion wear due to solid–liquid mixture has been investigated using a slurry erosion pot tester. Three different slurries namely fly ash, bottom ash and sand were used to carry out the erosion wear experiments. Four different pumping materials namely grey cast iron, stainless steel SS304, SS316L and super duplex stainless steel SDSS2507 were used. The erosion tests have been conducted on different slurry pump materials to establish the influence of rotational speed, particle size, solid concentration, time duration and materials type. The solid concentrations of erodent materials lie in range from 30 to 60% (by weight). The experiments were performed at four different speeds namely 600, 900, 1200 and 1500 rev/min with time duration of 90, 120, 150 and 180 minutes.

Erosion wear results of different pumping materials shows that the rank of material type was highest amongst rotational speed, time, solid concentration (wt. %) and average fineness number. Among from process parameters the rotational speed was the most influencing factor. Erosion wear of different coatings was found to be increased non-linearly with increase in time duration, rotational speed and solid concentration whereas decreased with increase in CF value. The erosion wear of different coatings follows power-law relationship with CF value. The increment of erosion wear was higher at initial phase of erosion wear experiments. It can be concluded that erosion wear process affects the particulate properties. The size of particle decreases after erosion wear experiments.

High-velocity oxy-fuel (HVOF) process was used to spray the different coating powders on pump materials. The WC-10Co-4Cr cermet powder was modified by addition of small proportion of Y_2O_3 , Mo_2C and ZrO_2 powders. The 3% addition Y_2O_3 and Mo_2C was helpful to improve the erosion wear resistance of WC-Co-Cr cermet coating. The order of erosion wear is found as: WC-10Co-4Cr+3% Y_2O_3 < WC-10Co-4Cr+3% Mo_2C < WC-10Co-4Cr < WC-10Co-4Cr+3% ZrO_2 .

In present investigation, the coating powders used was Ni-20Cr₂O₃, Ni-20Al₂O₃, Al-20TiO₂, Stellite-6 and Colmonoy-88. The maximum erosion was observed at 30° impact angle arrangement for Stellite-6 and Ni-20Cr₂O₃ coatings whereas at 60° impact angle for Colmonoy-88, Ni-20Al₂O₃ and Al-20TiO₂ coatings. It was found that the Stellite-6 and Ni-20Cr₂O₃ coating shows the ductile erosion wear whereas Colmonoy-88, Ni-20Al₂O₃ and Al-20TiO₂ showed the semi-brittle erosion wear behavior.

Microscopically, eroded surface of Stellite-6 showed the microcutting, plastic deformation, ploughing actions with few craters and lips. Colmonoy-88 surface underwent to craters, ploughing, carbide/boride pullout, fractures and intact. Erosion wear mechanisms on eroded surface of Colmonoy-88 were neither purely ductile nor brittle. The Ni-20Cr₂O₃ coating underwent to ploughing, microcutting, craters, ploughing, craters, ductile fractures. Micro-hills were visualized present on the eroded surface of Ni-20Cr₂O₃ coating at different locations. Simultaneously, the loosely bonded alumina grains were appeared on the surface of Ni-20Al₂O₃ coating by impact of erodent particles. Furthermore, no crack or splat debonding was observed on the surface which indicates the semi-brittle behavior of the coating. Commonly observed erosion wear mechanisms on the surface of Al-20TiO₂ coating were craters and ductile fractures which shows its semi-ductile behavior.

Erosion wear was successfully simulated by using an artificial neural network. The percentage error between experimental and ANN predicted erosion wear was found as ± 4.87 , 4.27 and 4.98% for sand, fly ash and bottom ash slurry which indicates the close agreement between neural network and experimental results.

Keywords: Erosion wear; Centrifugal slurry pump; Pump materials; SS304; SS316L; SDSS2507; Grey Cast Iron; Fly ash; Bottom ash; Sand; HVOF process; WC-10Co-4Cr, Colmonoy-88; Ni-20Al₂O₃; Al-20TiO₂., Stellite-6.

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NOMENCLATURE

Symbols	Descriptions
A	Area (m ²)
A_p	Area of particle (m ²)
A_t	Area exposed to erosion (m ²)
BH	Brinell hardness of target
C_w	Solid concentration (wt. %)
d_p	Particle diameter function (μm)
D	Erodent diameter (μm)
$D_{maxfret}$	Maximum Feret diameter
Er	Erosion wear (gm/m ²)
ER	Erosion rate (g/m ²)
$f(\alpha)$	Impact angle function
G	Gram molecular weight of target
H_v or H_t or $H.V.$	Vickers hardness of target
K	Material constant
K_c	Fracture toughness
L	Deformation depth
m	mass loss from the target surface
M_p or m_p	mass of erodent particle per unit time rate (g/sec)
N	Rotational speed (rev/min)
P	Perimeter (μm)
r	Particle radius (μm)
R^2	Regression coefficient
Ra	Surface roughness (μm)
Rq	Maximum peak in roughness testing length (μm)
Rz	Maximum – minimum roughness value (μm)
$S.F$	Size factor
S_k and S_m	Geometry constant
T	Time duration (min)
T_m	Melting temperature (°K)

u_p, U_p, V_p Particle velocity (m/sec)

V Velocity (m/sec)

Greek letters

α Impact angle (°)

ε Deformation factor

ε_m Erosion wear rate in terms of mass loss/impact mass

ε_{VP} Volumetric mass wear of material by single abrasive grain of particle

ε_{VT} Wear in terms of total volume removal

ρ_f Fluid Density

ρ_p Particle density

ρ_t Target density

ρ_m fluid mixture density

ψ Ratio of depth of contact to depth of cut

ψ Average sphericity

κ Solidity

χ Cutting wear factor

δ Deformation wear factor

Ω_c Critical strain for onset of lip formation

$\Delta\Omega_m$ Mean strain increment induced by each impact

ΔH_m Melting Enthalpy of target surface

σ deformation wear coefficients

γ Cutting wear

Superscripts

m or a Velocity exponent

n Concentration exponent

q or b Weight mean diameter exponent

Subscripts

p Particle

ch Convex hull

w Weight

Abbreviations

<i>ANN</i>	Artificial neural network
<i>CFD</i>	Computational fluid dynamics
<i>CF</i>	Circularity factor
<i>C.I.</i>	Cast iron
<i>COV</i>	Coefficient of variance
<i>EDS</i>	Energy dispersive spectroscopy
<i>B.A.</i>	Bottom ash
<i>F.A.</i>	Fly ash
<i>HVOF</i>	High-velocity oxy-fuel
<i>SEM</i>	Scanning electron microscopy
<i>PF</i>	Paris factor
<i>RD</i>	Roundness
<i>SDSS</i>	Super Duplex stainless steel
<i>XRD</i>	X-ray Diffractometry

CHAPTER 1

INTRODUCTION

CHAPTER 1

INTRODUCTION

Now-a-days, almost every engineering field is facing the problem of protecting the machinery from different types of damage or failures. The protection of various industrial machines, equipment and systems is recognized by many engineers, researchers and scientists. It requires a high level of process based understanding that involves in economic solution of such failure problems. The market of materials has grown at a high level at present time. A variety of materials are available which can withstand against different forces such as tensile force, compressive force, impact loading, fatigue loading etc. However, the degradation processes are found to be more aggressive for materials. So, the selection of material becomes a formidable task from the concern of performance, maintenance, and economy.

The adverse effect of material degradation processes is predominant in industrial as well social sector. Most common degradation processes are fatigue failure, erosion, corrosion, and abrasion. Among from these processes, the erosion and corrosion are found to be uncontrollable processes and affects almost every industry. Erosion and corrosion has been observed in reinforced concrete structures like bridges, river walls & gates, steel structure of building and construction industry, offshore structures, hydraulic machinery, gas turbines, heat exchanger tubes, engines and other industries.

The mining conditions are the most severing for the materials. Such conditions become more dangerous during the accelerated environment. The accelerated environment is imposed while the fast moving particles strikes to the materials at high velocities such as pump casings, impellers, nozzles, valve seats, tubes, tees, flanges, elbows etc. (Szala and Daniel, 2016; Rabinovich and Kalman, 2011). The schematic diagrams of damaged pump components are shown in Figure 1.1–1.3. The erosion wear is observed as a common problem of many industries such as oil & gas refinery, mining industry (sand-water slurries), thermal power plants (coal and coal-ash slurries). The parts of slurry transportation system such as pipes, impeller, shafts, casing etc. internally damages under the mechanical action of erosive particles (Postlethwaite et al. 1974, Gandhi et al. 1998, Gandhi et al. 2001, Lee and Lim, 2009).

Centrifugal slurry pump are widely used for transportation of homogeneous as well as heterogeneous slurries at medium and shorter distances. The slurry is a mixture of solid

immersed in liquid i.e. water or oil. Different types of slurries are transported by chemical, thermal and mining industries such as coal, oil, ashes, sand, metal tailings, etc. Many of the fluid contain abrasives and oxides which raises the material degradation problem such as abrasion, erosion and corrosion. In present study, the word “erosion wear” is an equivalent of “slurry erosion wear”.



Figure 1.1. Erosion wear on casing of centrifugal pump at actual condition [Noon and Kim, 2016, Electronic and printing permission of ©Elsevier].



Figure 1.2. Erosion wear on shroud of slurry circulation pump at actual condition [Qiu et al. 2015, Electronic and printing permission of ©Elsevier].



Figure 1.3. Cavitation erosion wear on radial impeller at actual condition (Szala et al. 2014).

1.1 CLASSIFICATION OF MATERIAL DETERIORATION PROCESSES

Material deterioration process i.e. wear is classified on the basis of many factors and attributes. A broad classification of wear is shown in Figure 1.4. Different types of material deterioration processes occur in slurry conveying systems due to the flow of slurry which have been discussed below:

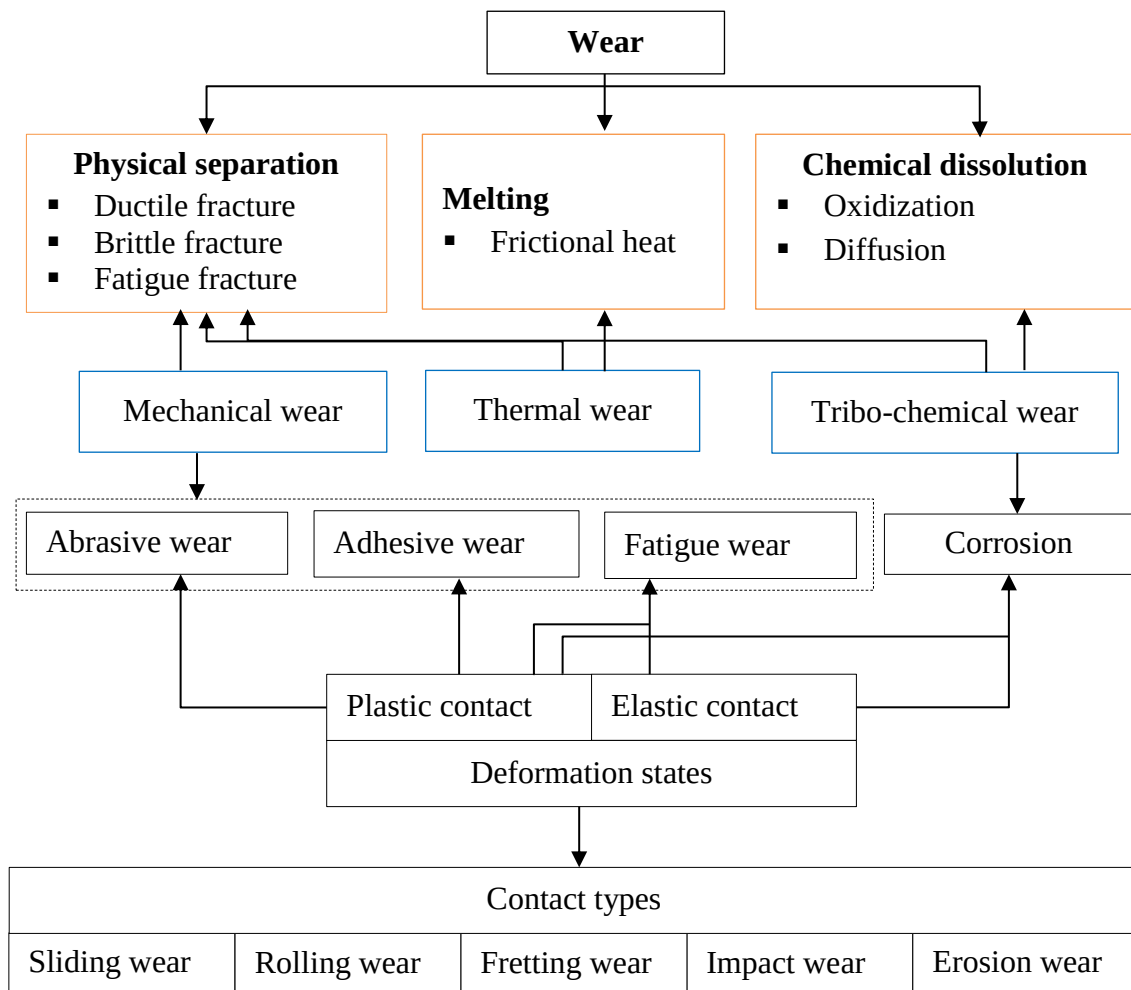


Figure 1.4. Classification of different wear processes (Kato and Adachi, 2001).

1.1.1 Abrasion

Abrasion is the cutting process in which the softer material is removed by the harder material. Hard abrasive particles or hard rough surfaces are responsible for abrasive wear of target materials. The remedy of abrasive wear is the decrease of surface fraction by utilizing a lubrication agent between hard and soft surface.

1.1.2 Adhesive Wear

Adhesive wear occurs while a material surface gets removed due to sliding of another surface. This happens due to the locking between both surfaces and/or due to bonding i.e. adhesive force between them. This is also known as frictional or galling wear. During this process, the yield stress on the material surface increases which results in plastic deformation. Adhesive between different surfaces take place due to irregularities or roughness. Adhesive wear can also be controlled by utilizing a lubrication agent.

1.1.3 Erosion Wear

It is material removal process which occurs due to mechanical action of moving particles with the target surface. The flowing particles transfer their kinetic energy to the target surface by the impact. Erosion wear depends upon a variety of parameters, such as velocity, time, concentration, impingement angle, target properties, etc. (Gandhi et al. 1998, Gandhi et al. 2001, Desale et al. 2006, Goyal et al. 2012). This is a major problem in mining industries, ash disposal system and hydropower plants. In ash disposal systems when high velocity ash particle interact with the surface erosion wear takes place. This type of erosion can be controlled by improving surface property of target material and controlling the interaction of erodent and target material. Erosion resistance of materials can be improved by hardfacing, thermal spray coating, cladding and surface treatment.

- Cavitation erosion takes place while the solid and liquid are in relative motion. Due to the relative motion, bubble formation occurs. The bubbles moves and collapse against the target material. Due to the collapse of bubbles, a large pressure force is exerted by the small area of target material. It mainly occurs in fluid transport system, turbine components, pumps, marine, etc.
- Liquid impingement erosion is caused due to repeated impact of slurry particles with the target surface. During this process, the small liquid bodies which are distinct in nature generate the impulsive forces on the small region of target surface. This result in increase of yield strength and endurance limit of the target material which tends to destroy the material.

1.1.4 Surface Fatigue

Stresses caused by periodic motion of mechanical machinery which leads to fatigue. The failure due to rolling or sliding of one body over another body and of surface is known as surface fatigue wear. The increase in yield stress causes the formation of micro-cracks which leads to surface failure. Cracking start below the surface and reach to the surface as shear stress reach its maximum limit. Basically, fatigue wear depends upon the number of loading and unloading cycle.

1.1.5 Corrosion

This process is caused due to electro-chemical reaction of surface materials with the fluid/working environment. As the surface of the material reacts with the fluid, it causes the weakening of the surface which results in degradation of target material. Corrosion is also a continuous process like erosion wear. Corrosion and erosion occur together in all the slurry erosive environments. In initial years, the scientific researchers focused on corrosive wear but erosion is the more critical factor than corrosion (Postlethwaite et al. 1974). The material failure due to corrosion is caused by the electrochemical reaction that can be controlled by using appropriate procedures (Lee and Lim, 2009; Xiao-Yan and Tao, 2005; Rajahram et al. 2011).

Table 1. 1: Types of wear, wear symptoms and appearance of worn-out surfaces

Types of Wear	Symptoms	Appearance of the worn out surface
Abrasive	Cut out by abrasive particles presence of clean furrows	Groves
Adhesive	Metal transfer from surface is a prime Symptom	Torn out, catering and seizure surfaces
Corrosion	Presence of metal corrosion constituents	Depressions or rough pits
Erosion	Presence of hard abrasive particles in the fast moving slurry/fluid and short abrasion furrows	Troughs and waves
Fatigue	Presence of surface and sub-surface cracks in mating surfaces accompanied by pits and spalls	Sharp and short angular edges around pits

In actual practice, erosion wear contributes majorly as compared to corrosion in material degradation. Erosion wear rate decrease the service life of slurry conveying system and

affected the overall efficiency of plant. Slurry suspended particle causes erosion wear in hydraulic machinery likes pumps, pipes, pipe fitting, ducts, nozzles, turbine and its components (Mansouri et al. 2014, Mansouri et al. 2015; Vieira et al. 2016). Erosion wear increases as the flow rate of the slurry is increases due to increase in kinetic energy of suspended particles with high force on the target surface. Erosion wear due to ash particle suspended in the air as ESP, ID fan components is challenging task to control volumetric mass in many engineering applications. The various types of wear, with recognized symptoms and appearance of worn out surfaces are given in Table 1.1.

1.2 MECHANISMS OF EROSIWE WEAR

Erosion wear is the material degradation process that occurs due to continuous impingement of solid slurry particles. Slurry erosion wear in different materials takes place by the relative motion between slurry particle and solid surface through the erosive action. Solid particles impacts on the material surface and material failure take place one of the mechanism either directional impact or random-collisions. In initial phase, slurry suspended particles impact on the target surface which results in plastic deformation. Second phase is established due to continuous impingement of particles on the surface of material and material removal takes place due to the relative movement of solid particles with solid surface which tends toward the mechanical failure of target surface. The components are made up of ductile and brittle materials so, the erosion wear occurs in different components is significantly different. Erosion wear of the materials takes place mostly by microcutting, ploughing, lip formation and impact of particulate (Zum-Gahr, 1987), as shown in Figure 1.5.

In initial years, erosion wear of ductile materials was studied in which-microcutting action is responsible for erosion wear in ductile materials (Finnie, 1958, 1960). The craters build up while the particles strike the target at a low impact angle. Material pile up builds while the particles strike at high impact angles which get removed by rapid collisions particles. Generally, the erosion wear occurs in ductile materials is high in initial phase and retards after a passage of time. The mode of failure on material surface in terms of material hardness may be either brittle failure or ductile failure (Bitter, 1963, Sundararajan, 1991). Erosion wear in brittle materials generally occurs due to crack formation. While the particles strike on the brittle materials, the cracks start forming on its surface. Rapid striking of particles tends towards growth of cracks and material deteriorates.

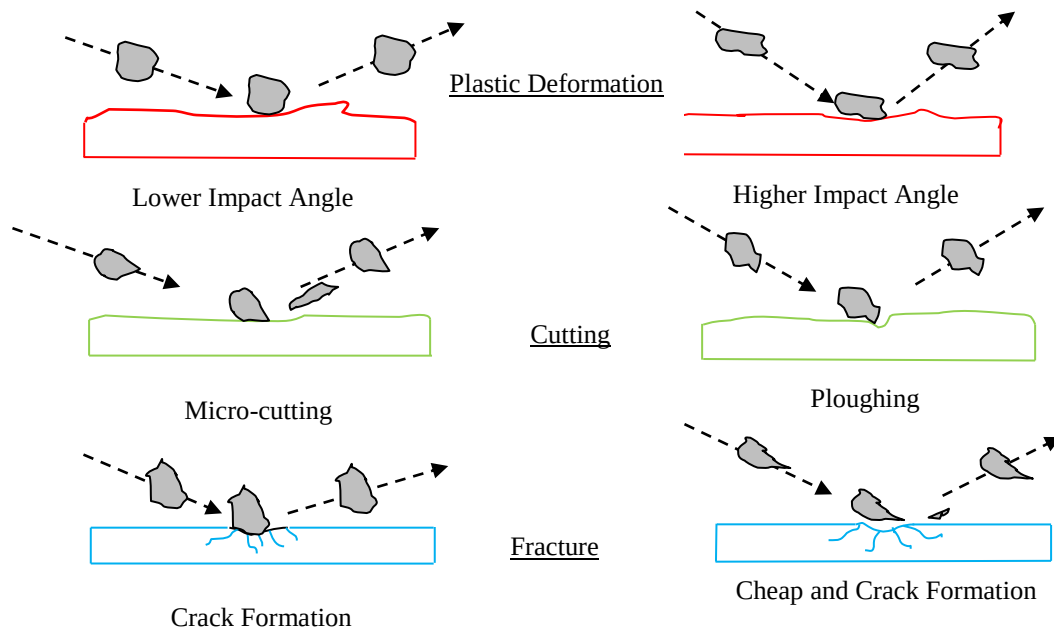


Figure 1.5. Erosion wear mechanisms.

1.3 SLURRY PUMP

Pump is the heart of any slurry transportation system. So, the overall efficiency of slurry transportation system depends upon the performance of slurry pump. A slurry pump is widely used for transportation of liquids as well as solid-liquid mixtures in many chemical and mining industries. Generally, centrifugal and progressive-cavity slurry pumps are used for the transportation of slurries. Performance of pump depends upon anonymous parameters, few of them are; slurry concentration, slurry viscosity, physical properties of solids, acidic nature of slurry etc. In general, the performance of pump can be estimated by pumping the clear water. Many of the researchers have made efforts to understand the flow mechanism in slurry pumps for the flow of clear water and solid-liquid slurry. Design parameters play a vital role in estimation of pump performance. The design of slurry pump is usually same as conventional pump but it has wider space between vanes for the flow of dense slurry. The material of pump and its components play a vital role in reliable transportation of solid-liquid mixture. Stainless steels or cast iron are universally accepted pumping materials (Neville et al. 1995). The erosion wear in such components can be controlled by increasing the surface hardness of materials (Goyal et al. 2012).

Slurry pump is used in many industries to serve different duties such as in oil and gas refinery, in drug industry to pump different chemicals, in mining industry to pump sand-water slurries, in thermal power plants to pump coal-water or coal oil slurry, in slurry transportation system of thermal power plant to pump coal-ash slurries.

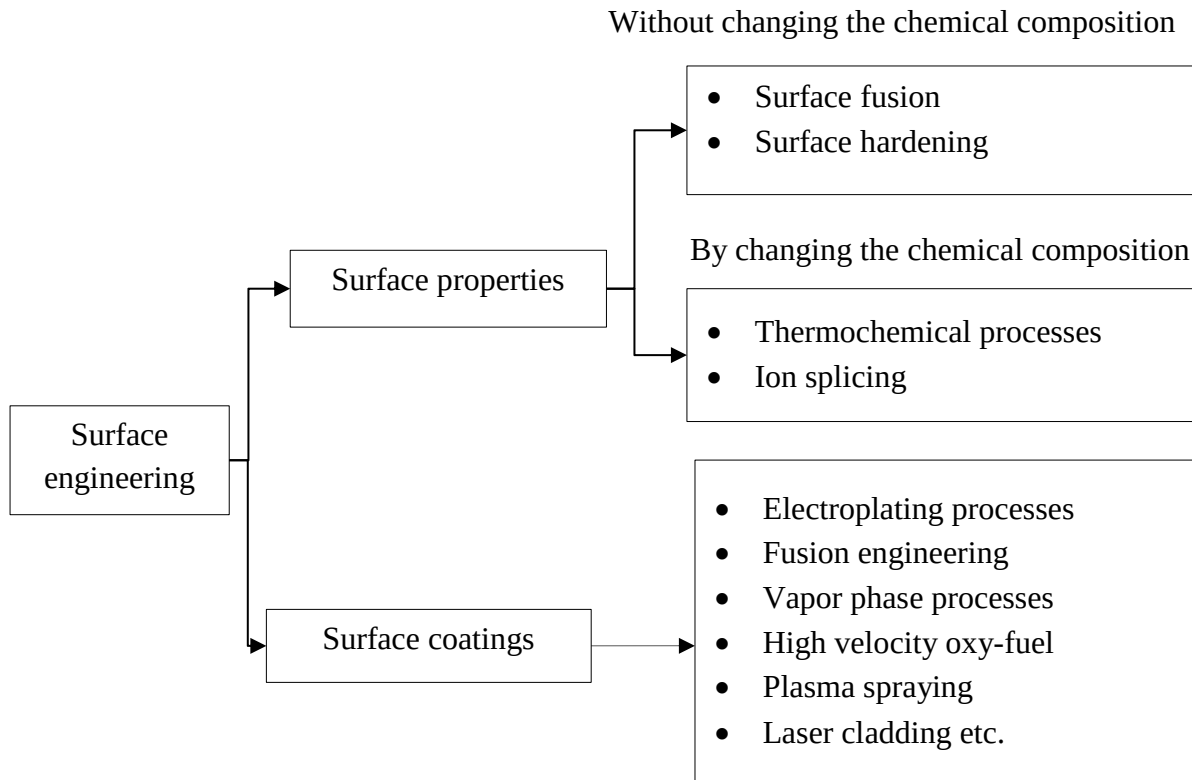


Figure 1.6. Various surface modification processes (Hutchings, 1992).

1.4 EROSION WEAR REMEDIES

Surface engineering is a universally used technology which is applied to various industrial applications. It includes various techniques, methods and processes which can be applied to modify the surface properties to achieve the desired performance against applied environment such as mechanical stresses and fatigues, under-water conditions, tribology, biological reactions etc. (Datta and Gray, 1993). The different types of surface modification processes are classified in Figure 1.6. Among from all surface modification techniques, coating deposition techniques were widely adopted by industries and economic sector for the protection of various components of machinery and to improve the life. Coating is a layer that is applied to the surface of an object, usually referred as substrate.

Erosion wear of materials can't be prevented but it can be minimized by changing the surface properties. Most of the metals easily eroded unless they are provided with the protection by means of human endeavor. Method of minimizing the erosion wear have been illustrated elsewhere (discussed in Chapter 2). Many factors contribute in minimizing the erosion wear such as design of components, selection of materials, environmental control,

application of coatings etc. Erosion testing, monitoring and inspection are crucial for minimizing the erosion wear. The model for minimizing the erosion wear is illustrated in Figure 1.7.

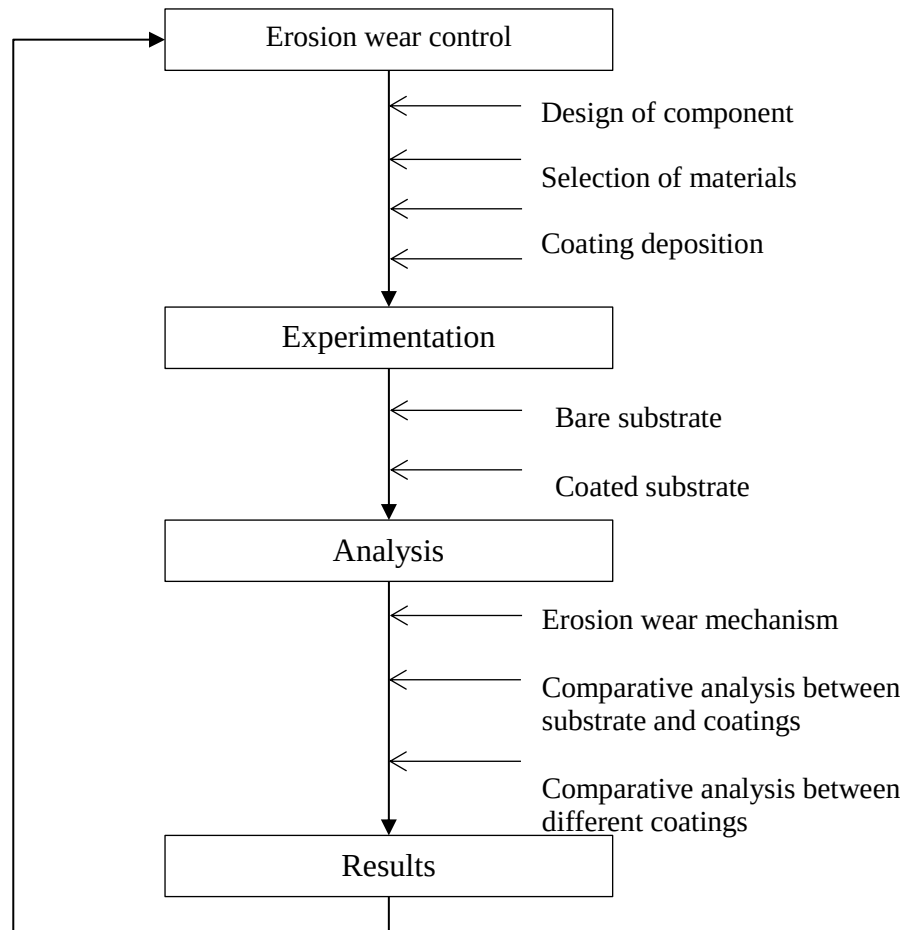


Figure 1.7. Flow chart of process monitoring of erosion wear.

1.4.1 Design

Optimum design of a particular component contributes in minimizing the surface erosion wear. Various design parameters that contribute in minimizing the erosion wear which are discussed below:

- Inadequate drainage
- Shape bends
- Irregularities in surface
- Surface finish
- Maintenance design etc.

During the design process, the environmental factors such as pH, dissolved elements, velocity and concentration are also taken into account.

1.4.2 Selection of materials

Selection of materials is an essential part of erosion wear controlling. In erosion wear, the material properties such as microhardness, toughness, elasticity, ductility plays an important role. But these parameters are insufficient because the material component wouldn't be subjected only to particles but also to the mechanical loadings. So, the other material properties play a crucial role. Many conflicting requirements like appearance, ease of fabrication, availability and mechanical properties affects the selection of material.

1.4.3 Coating deposition

Different types of coatings have been used to minimize the erosion wear (already discussed in Chapter 2). The coatings are classified into the three categories, as follows:

- *Metallic coatings*: Electro deposition, hot dipping, cladding, diffusion, laser alloying, thermal spraying.
- *Inorganic coatings*: Anodizing, phosphating, cermet thermal, spraying.
- *Organic coatings*: Conventional paints, epoxy coatings, bitumen, rubber, plastic lining.

1.4.4 Characterization of flowing solid

Microstructure and phase characterization of erodent is also important part of erosion wear assessment. The microstructure analysis provided the shape details which enables the erosion wear.

1.5 MOTIVATION BEHIND PRESENT STUDY

Erosion wear is a crucial problem which is associated with the flow of different slurries. Erosion wear becomes dominant at accelerated conditions therefore; it shortens the life of equipment. Slurry erosion is found most common in mining, chemical industries and thermal power plants. Major worn-out equipment in different industries are pump casings, impellers, nozzles, valve seats, tubes, tees, flanges, elbows etc. Most dangerous accelerated conditions are observed at pump casing and impeller. Usually, centrifugal slurry pumps are used to transport the different slurries in industrial sector. Also, the erosion wear due to gas-solid is relatively well understandable than solid-liquid erosion. Jet-impingement test method is

standard method to evaluate the erosion wear due to gas-solid flow (recommended by ASTM G76–95). However, slurry pot tester was recommended by Desale et al. (2006) to evaluate the erosion wear in pump and pipelines for the flow of solid-liquid slurry. So, there is a need to evaluate the erosion wear of different pump materials for the design purpose.

The erosion wear of materials depends on the variety of parameters that comprises properties of flowing medium and material, and process parameters. A small variation in any of the parameter affects the erosion wear process. Hence, the present study is also aimed to investigate the physical and chemical properties of erodent materials.

The life of pump/component can be improved either by changing the design if component or by changing the selection of material or by changing the surface properties. The surface modification technique is preferred in present study to improve the erosion wear performance of pump materials. HVOF spraying process is the most versatile coating deposition process among the different processes. HVOF process can be used for pure metals as well as ceramics/cermets (Szala and Tadeusz, 2013, Szala et al. 2014). In present study, ceramics and cermets are used to improve the erosion wear performance of pump materials. So, HVOF process is highly preferable in such cases.

Use of optimization and prediction tools has attracted the most of researchers because it saves cost as well as time. This also motivated the author to optimize the erosion wear by using a prediction-cum-optimization tool. Design of experimentation tools are widely used by different researchers. But design of experiments techniques hides any ground truth underlying behind the problem. Now-a-days, the use of artificial intelligence is not limited to few applications. In this context, an artificial intelligence (artificial neural network) tool has been used to present a prediction model which could be helpful to simulate the erosion wear results.

1.6 THESIS OUTLINE

Different facets of present work written in thesis are divided into eight chapters. The brief content of the each chapter is given below:

Chapter 1 presents general introduction about various aspects of erosion wear in pump materials. This chapter also covers the types of wear, mechanisms of erosion wear, and different techniques to minimize the erosion wear of different materials.

Chapter 2 presents the literature review related to erosion wear of different materials and coatings. This chapter also comprises the literature about different erosion wear testing

methods, parameters affecting erosion wear, different types of bench scale test rigs and different thermal spraying processes.

Chapter 3 explains the research methodology adopted to carry out dissertation work. This chapter also presents the characterization of erodent materials and solid-liquid slurry along with the information about selection of materials, collection of samples, bench scale equipment, testing methods, and simulation techniques. This chapter also explains the various properties of erodent materials such as surface morphology, chemical composition, distribution, particle size/shape, porosity of erodent materials, static settled concentration, specific gravity, bulk density, pH value, and crystalline structure.

Chapter 4 summarizes the erosion wear observations of four different pumping materials using three different erodents namely fly ash, bottom ash and sand. The effect of parameters namely rotational speed of propeller, particle size, impact angle and solid concentration is also discussed. The most influencing factor has been analyzed by using design of experiments technique.

Chapter 5 covers the investigation of various properties such as microstructure, crystalline phases of as-sprayed coatings, roughness, crack toughness and microhardness of different coatings. This chapter also gives a comparison of erosion wear on the surface of different cermet coatings. The WC-Co-Cr cermet coating is modified by adding a small amount of ceramics. The synergistic effect of addition of ceramics on erosion wear of cermet coating is also explained in this chapter.

Chapter 6 covers the erosion wear of metal composite coatings. In this chapter, the erosion of analysis of various metal powder composite coatings is made and certain modifications were done to improve their erosion wear performance. Various coating properties are also investigated such as microstructure, crystalline phases of as-sprayed coatings, roughness, crack toughness and microhardness.

Chapter 7 represents the use of artificial neural network (ANN) tool to develop a prediction model for simulation of erosion wear results. The experimental erosion wear results are compared with the predicted results.

Chapter 8 lists the broad conclusions drawn on the basis of present investigation and recommendations for future work.

CHAPTER 2

LITERATURE OVERVIEW

A number of researchers have investigated the erosion wear of different materials with influence of various factors. In this context, an overview is carried out with an objective for providing inclusive literature survey about different parameters on which erosion wear of pumping materials and coatings depends. This chapter covers the evolution of slurry pot testers, various factors affecting erosion wear, erosion wear of different material and coatings.

2.1 DESIGN AND DEVELOPMENT OF VARIOUS EROSION WEAR TEST RIGS

Investigators have used different types of test rigs for conducting the slurry erosion wear experiments. Many years ago, Zu et al. (1990) had designed a slurry erosion tester. A schematic view of the erosion tester is shown in Figure 2.1. This tester consists of water tank, ejector, three-stage pump, vertical suction tube, exit nozzle, transparent perspex test chamber and specimen holder.

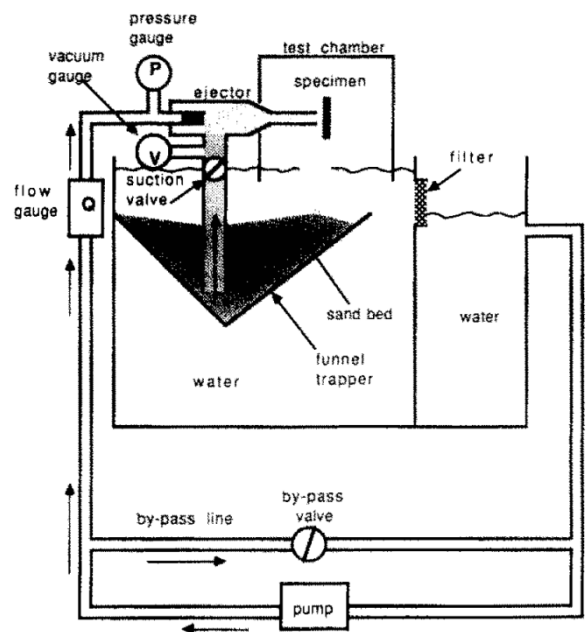


Figure 2.1. Air-operated diaphragm pump operated slurry jet erosion tester developed by Zu et al. (1990) [Electronic and printing permission of ©Elsevier].

Gandhi et al. (1999) performed the erosion wear experimentation on steel by using jet pot tester for sand-water slurry. A schematic view of the erosion tester is shown in Figure 2.2(a). The capacity of pot tester was 3.8 L. The main components of this pot tester were motor, shaft, cylindrical tank, rotating arms, stirrer arrangement, bearings, test fixtures etc. They also fabricated a fixture by using hardened carbon steel (hardness=RC 45) to mount the work pieces. The geometry of the fixture is shown in Figure 2.2(b).

Figure 2.2. Slurry erosion tester developed by Gandhi et al. (1999) [Electronic and printing permission of ©Elsevier].

Erosion pot tester was widely used to examine erosion wear performance of material rotational method. On this basis, Iwai et al. (2009) used micro-slurry-jet erosion tester to evaluate intrinsic wear properties. Pot tester was used to evaluate the effect of rotational speed, particle size and shape, solid concentration, time duration and standoff distance on target surface. On Pin-on-disk test rig sliding erosion wear were determined, schematically illustrated in Figure 2.3.

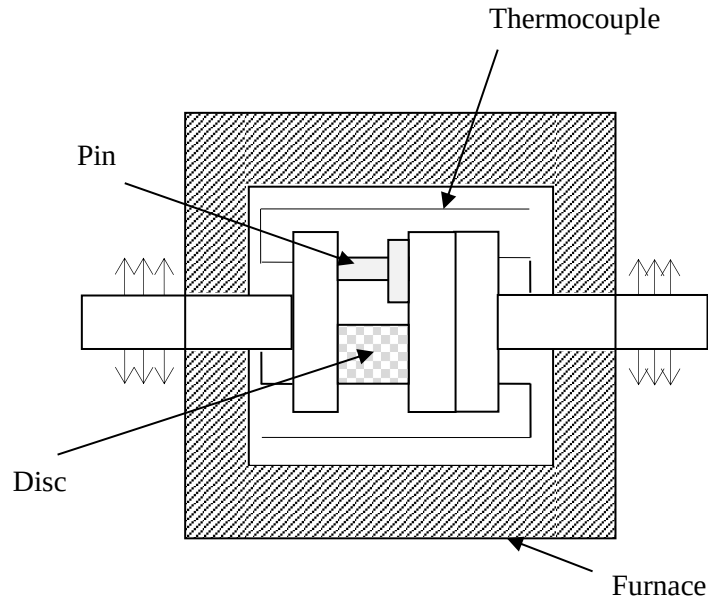


Figure 2.3. Schematic illustration of Pin-on-disk test rig (Iwai et al. 2009).

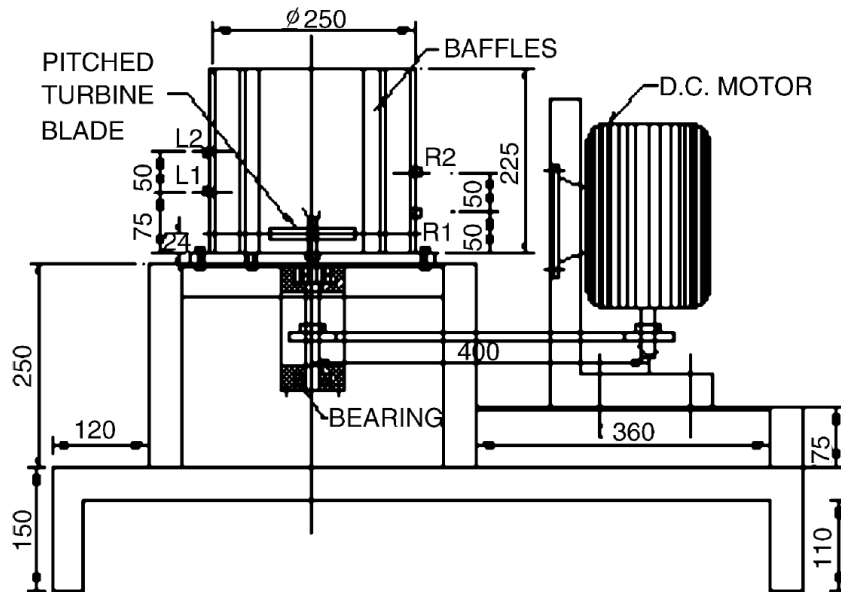


Figure 2.4. Schematic illustration of slurry pot tester rig tester developed by Desale et al. (2005) [Electronic and printing permission of ©Elsevier].

Desale et al. (2005) used slurry pot tester to evaluate the erosion wear of different materials. The slurry pot tester consists of a transparent cylindrical tank having diameter of 240 mm. The cylindrical tank had four baffles of size 25mm×10 mm. The other components of pot tester were a propeller, two bearings, an oil seal, belt pulley drive and a 0.75 kW DC motor.

A schematic illustration of this pot tester is shown in Figure 2.4. This pot tester was helpful to measure the erosion wear at high solid concentrations.

More et al. (2014) modified an erosion wear pot tester developed by Desale et al. (2005) and evaluated the effect of impact angle, as shown in Figure 2.5. They developed an arrangement to replace the drill machine for adequate rotation. The components of this pot tester was same as tester used by Desale et al. (2005) but the only change was use of 0.6 kW DC motor to replace the use of drill machine.

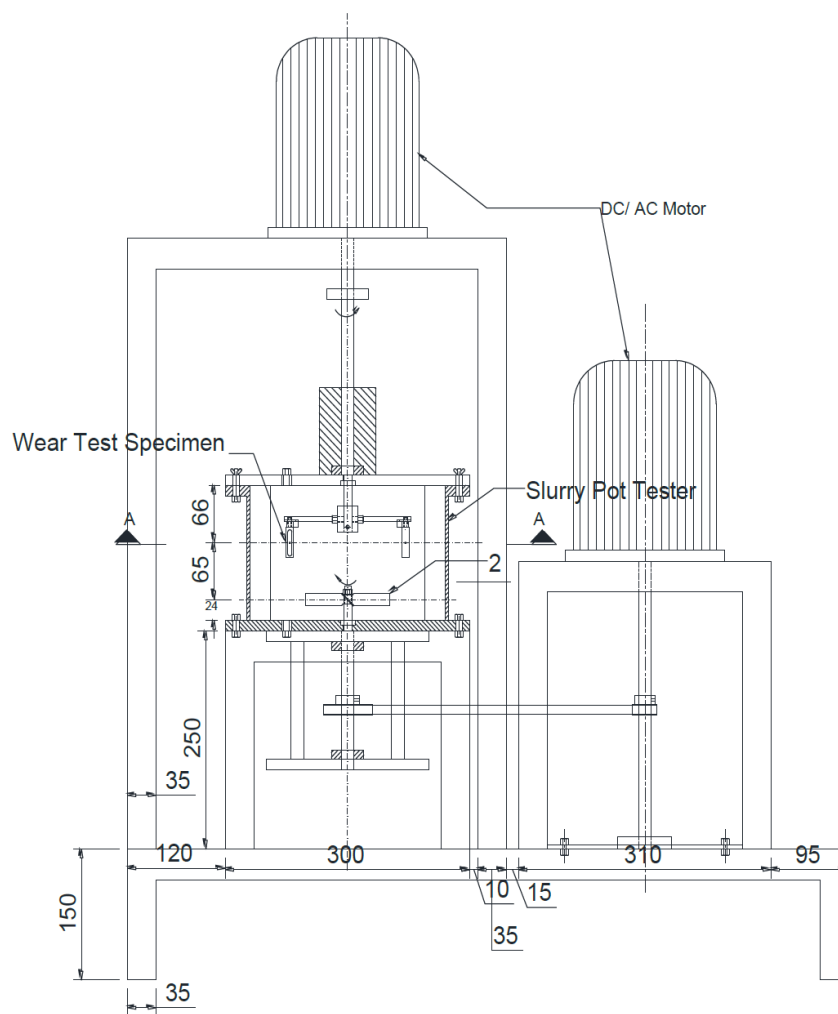


Figure 2.5. Schematic illustration of slurry pot tester rig tester modified by More et al. (2014).

Walker and Robbie (2013) had used a slurry jet tester which uses an air-operated diaphragm pump to circulate the slurry, as shown in Figure 2.6. It consists of a recirculating slurry loop which is connected to diaphragm pump. Diaphragm pump also ensures the velocity and flow through the nozzle. This tester can be used to evaluate the erosion wear at high velocities.

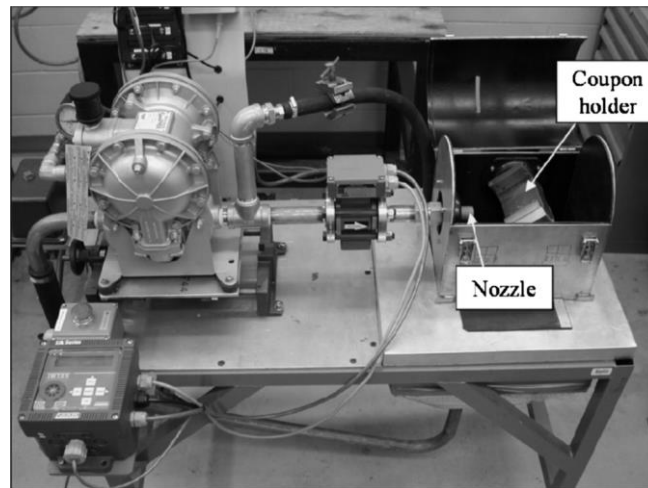


Figure 2.6. Air-operated diaphragm pump operated slurry jet erosion tester by Walker and Robbie (2013) [Electronic and printing permission of ©Elsevier].

Xie et al. (2015) developed a NRC slurry jet erosion tester. They evaluated the resistance of different materials against slurry at various impact angles. The components of NRC slurry jet erosion are shown in Figure 2.7.

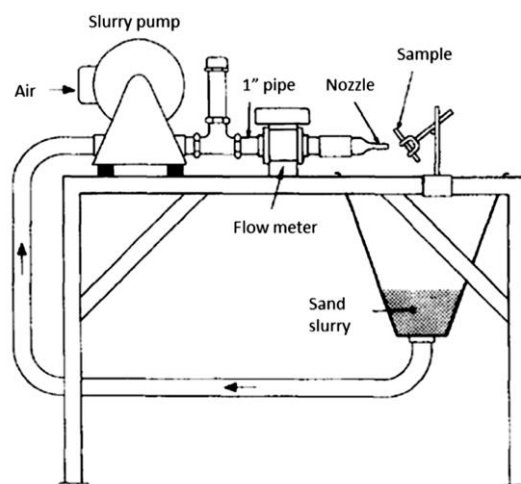


Figure 2.7. Schematic diagram of NRC slurry jet erosion tester by Xie et al. (2015) [Electronic and printing permission of ©Elsevier].

Literature indicates that the field experiments were conducted to determine the erosion wear in actual working conditions but there are many process-influencing parameters like time duration, material and uncontrollable testing variable with high cost of experimentation (Anderson et al. 2004; Walker and Robbie, 2013; Parent and Li, 2013; Xie et al. 2015). So, the use of pot tester is cost beneficial also, it provides detailed results with variation if influencing parameters.

In this section, different types of slurry erosion tester used by different investigators have been discussed. Among these rigs, Jet erosion test rig is highly applicable to evaluate the effect of impact angle on target specimen and provide with high accuracy convenient method but its drawback is that the generated data mismatches field data. Another drawback of jet erosion test rigs is that they are operated at low concentration only. At present time the high slurry transportation systems are used. In such conditions, the erosion wear data from jet tester mismatch the actual field results. On the other hand, pot tester is high effective to evaluate erosion resistance with variation of solid concentration and rotational speed. Pot testers can be used to investigate erosion wear different type of flow types of flow with some modification. Also, the jet-impingement test method is standard method to evaluate the erosion wear due to gas-solid flow (recommended by ASTM G76–95). However, slurry pot tester was recommended by Desale et al. (2006) to evaluate the erosion wear in pump and pipelines for the flow of solid-liquid slurry.

2.2 PARAMETERS AFFECTING THE EROSION WEAR

Erosion of a material depends upon a large number of parameters such as properties of particles, properties of target material and process parameters. Elkholy (1983) had proposed a correlation which used to determine the erosion wear of different materials:

$$Ew = k \times V^m \times d^n \times C^q \quad (2.1)$$

In above equation, the term ‘ V ’ denotes the velocity of particles, ‘ d ’ denotes the weighted mean diameter of particles and ‘ C ’ denotes the solid concentration of slurry. The symbols ‘ m ’, ‘ n ’ and ‘ q ’ are the exponents. These parameters are the most contributing parameters among others. Many of the other investigators have discussed the erosion wear models on the basis of different parameters which are discussed in Table. 2.1.

Table 2.1: Erosion wear models on the basis of different parameters

Investigators	Erosion wear models
Tabor et al. (1951)	$\varepsilon_m = \frac{6.5 \times 10^{-3} V_p^{2.5} \rho_p^{2.5}}{C_p T_m^{0.75} H_t^{1/4}} \quad (2.2)$
Sheldon and Kanhere (1972)	$\varepsilon_{VT} = \frac{d_p^3 V_p^3 \rho_p^{3/2}}{H_v^{3/2}} \quad (2.3)$
Jennings et al. (1976)	$\varepsilon_V = \frac{K_T^{3/2}}{R} \frac{G^{1/3}}{\rho_t^{1/3} k.T_m \Delta H_m} \quad (2.4)$
Hutchings et al. (1976)	$\varepsilon_V = 5.82 \times 10^{-10} V_p^{2.9} \quad (2.5)$
Evans et al. (1978)	$\varepsilon_{VP} = \frac{V_p^{2.9} r^{11/3} \rho_p^{1/4}}{K_c^{4/3} H_t^{1/4}} \quad (2.6)$
Hutchings et al. (1981)	$\varepsilon_m = 0.033 \frac{\alpha \rho_t P^{0.5} V_p^3}{\Omega_c^2 H_t^{1.5}} \quad (2.7)$
Reddy and Sundararajan (1986)	$\varepsilon_{VP} = \frac{L^3 \Delta \Omega_m}{\Omega_c} \quad (2.8)$

The detailed discussion on effect of different parameters on erosion wear of different materials studied by various investigators by using different test rigs is as follows:

2.2.1 Velocity of Solid Particles

Erosion wear of the materials also varies with velocity of particles. Erosion wear is a function of the kinetic energy of the slurry suspended particles which interact to target surface (Hawthorne et al. 2002). Particles that impact the target at very particular velocity results in transfer of kinetic energy with target material, hence a slight surface deformation. Small fraction of particles has adequate kinetic energy for induce permanent deformation of target surface. However, the more particles attain the required threshold energy with increase in velocity which results higher surface deformation rate (Deng et al. 2005; Divakar et al. 2005; Rajahram et al. 2009; Rajahram et al. 2011; Islam et al. 2015). The erosion wear is directly proportion to velocity of particle:

$$-\frac{dm}{dt} = kV^a \quad (2.9)$$

Where, t is time period of investigation process, m is mass loss from the target surface, k is experimental constant and velocity exponent is n (2 to 5 for different materials). Finnie

(1958) had recommended velocity exponent n is equal to 2. Gupta et al. (1995) performed erosion wear experimentation on brass and mild steel and developed correlation by using Equation 2.1, as written below:

$$Ew_{Brass} = 0.178 \times V^{2.4882} \times d^{0.291} \times C^{0.516} \quad (2.10)$$

$$Ew_{mildsteel} = 0.223 \times V^{2.148} \times d^{0.344} \times C^{0.556} \quad (2.11)$$

Gandhi et al. (1999) performed the erosion wear experimentation on steel by using pot tester for sand-water slurry. They found that velocity was the most influencing parameter for erosion wear and value of velocity exponent as 2.6.

Clark and Hartwich (2001) evaluated that erosion was proportional to the square of velocity and inversely proportional to hardness. They found that the increase in velocity of slurry particle increase impact energy which is responsible of higher erosion rate.

Deng et al. (2005) studied the effect of impact angle and velocity on erosion wear for ASTM A106. They conducted the erosion wear experiments by varying the impact angle in range 10–90° and velocity 19.2–40.2 m/s using Olivine sand as erodent materials. They found that erosion wear of the target surface increases with increase in velocity of solid particle interaction on metal surface.

Padhy et al. (2009) investigated the effect of velocity on erosion wear of turbine buckets. They carried out the erosion wear analysis by using sand having particle size 90–180 µm and velocity of jet in range 5000–10000 rev/min. They calculated the erosion wear by using power law and value of velocity index was found as 3.79.

Kumar et al. (2017) also performed an experimental study on slurry erosion of different pipeline materials namely mild steel, SS304 and SS202. They developed correlations to evaluate the erosion wear of mild steel, SS202 and SS304, as written below:

$$Ew_{mildsteel} = 0.223 \times V^{2.06} \times d^{0.414} \times C^{0.642} \quad (2.12)$$

$$Ew_{SS304} = 0.223 \times V^{1.69} \times d^{1.69} \times C^{0.537} \quad (2.13)$$

$$Ew_{SS202} = 0.27 \times V^{1.53} \times d^{0.295} \times C^{0.515} \quad (2.14)$$

Many of the other investigators (Manisekaran et al. 2006; Tian et al. 2009; Islam et al. 2015) have found that erosion wear increases with increase in impingement velocity of slurry particles. Investigators also found that velocity of the abrasive particle is most dominating factor for slurry erosion wear.

2.2.2 Impact Angle

Impact angle is defined as the angle between the target surfaces to the normal velocity component of solid particle. Surface deformation or erosion wear of material varies with the variation of impact angle. Since 1957, wear correlations have rapidly changed but no equation has been found yet that can satisfy all the conditions or parameters for erosion wear. Fundamental equation helps in predicting erosion wear rate or mass loss with high precision. At present time, many researchers are using same or modified correlation that is given by Finnie (1960). Empirically, significant effect on erosion wear rate with respect to velocity of erodent was determined as:

$$E \approx k \times M_p \times V^a \times f(\alpha) \quad (2.15)$$

Where, the value of n is varies within a range 2 to 3 (Faddick, 1982). Finnie (1960) represented the function $f(\alpha)$ as:

$$f(\alpha) = \begin{cases} (\sin 2\alpha - 3 \sin^2 \alpha) & \text{for } \alpha \leq 18.5^\circ \\ \frac{1}{3} \cos^2 \alpha & \text{for } \alpha > 18.5^\circ \end{cases} \quad (2.16)$$

Haugen et al. (1994) represented the function $f(\alpha)$ for steel grades as follows:

$$f(\alpha) = \sum (-1)^{i+1} A_t \left(\frac{\alpha \pi}{180} \right)^i \quad (2.16)$$

The other erosion wear models developed by different researchers on the basis of particle motion and target's properties are summarized in Table 2.2.

Table 2.2: Erosion wear models based on particulate motions and target's properties

Investigators	Numerical model
Finnie (1958)	$\varepsilon_{VP} = \begin{cases} \frac{m_p V_p^2}{P_{\psi k}} \left(\sin 2\alpha - \frac{6}{k} \sin^2 \alpha \right) & \tan \alpha \leq \frac{K}{6} \\ \varepsilon_{VP} = \frac{m_p V_p^2}{P_{\psi k}} \left(\frac{k \cos^2 \alpha}{6} \right) & \tan \alpha \geq \frac{K}{6} \end{cases} \quad (2.17)$
Bitter (1963)	$\varepsilon_{VP} = \frac{1}{2} \frac{M(V_p \sin \alpha - K)^2}{\delta} \quad (2.18)$
Bitter (1963)	$\varepsilon_{VC} = \begin{cases} \frac{2M(V_p \sin \alpha - K)^2}{\sqrt{V_p} \sin \alpha} \left(V_p \cos \alpha - \frac{C(V_p \sin \alpha - K)}{(V_p \sin \alpha)^2} \chi \right); & \alpha \geq \alpha_{p0} \\ \frac{\frac{1}{2}M[V_p^2 \cos^2 \alpha - K_1(V_p \sin \alpha - K)^{3/2}]}{\chi}; & \alpha \leq \alpha_{p0} \end{cases} \quad (2.19)$
Neilson and Gilchrist (1968)	$\varepsilon_{VC} = \begin{cases} \frac{\frac{1}{2}M(V_p^2 \cos^2 \alpha - V^2 r)}{\chi} + \frac{1}{2} \frac{M(V_p \sin \alpha - K)^2}{\delta}; & \alpha \leq \alpha_{p0} \\ \frac{\frac{1}{2}M(V_p^2 \cos^2 \alpha)}{\chi} + \frac{1}{2} \frac{M(V_p \sin \alpha - K)^2}{\delta}; & \alpha \geq \alpha_{p0} \end{cases} \quad (2.20)$
Wallace et al. (2000)	$E = \begin{cases} \frac{\left(\frac{1}{2}u_p^2 \cos^2 \alpha \sin 2\alpha\right)}{\gamma} + \frac{\left(\frac{1}{2}u_p^2 \sin^2 \alpha\right)}{\sigma} & \alpha \leq 18.5^\circ \\ \frac{\left(\frac{1}{2}u_p^2 \cos^2 \alpha\right)}{\gamma} + \frac{\left(\frac{1}{2}u_p^2 \sin^2 \alpha\right)}{\sigma} & \alpha > 18.5^\circ \end{cases} \quad (2.21)$
Where γ is the cutting wear having the value 33316.9 and σ is deformation wear coefficients equal to 77419.7.	

Many of the other researchers (Burstein and Sasaki, 2000; Deng et al. 2005; Divakar et al. 2005; Al-Bukhaiti et al. 2007; Tian et al. 2007; Krishnamurthya et al. 2012; Sun et al. 2015) reported the effect of the impact angle and variation in erosion wear as function of properties of target material. Finnie (1960) reported that erosion wear of a particular material depends on nature of the material either ductile or brittle. He had defined the impact angle as high and low impact angle on the basis of some assumptions. He had found that negligible erosion wear occurs at normal impact conditions. The erosion wear of ductile materials and brittle materials on the basis of impact angle has been discussed follows.

▪ *Erosion wear of ductile materials on the basis of impact angle:*

In earlier years, Oka et al. (1997) examined the erosion wear carbon steel on the basis of assumption made by Finnie (1960). They found that the highest peak of erosion wear for ductile material was observed at 15 to 45° impact angle.

Gandhi et al. (2001) performed an experimentation using pot tester to analyze the effect of particle impingement angle on erosion wear of Brass pieces. The orientation or impact angle was varied from 0° to 90° and concentration range was 20-40% by weight. They found that as the orientation angle increases erosion wear decreases. They also found that the erosion wear was increased with increasing the angle up to 30° and decreases afterwards till 90° for various range of velocities and particle sizes.

Desale et al. (2006) studied the effect of impact angle on erosion wear for ductile materials AA6063 and AISI 304L steel. They used quartz, alumina and silicon carbide as erodent materials for erosion wear investigation. The experimentation was performed at different impact angles that range from 7.5-90°. They found that erosion wear of AA6063 steel sample was greatest at 15° and decreases as the angle increases upon 90° as seen in Figure 2.8.

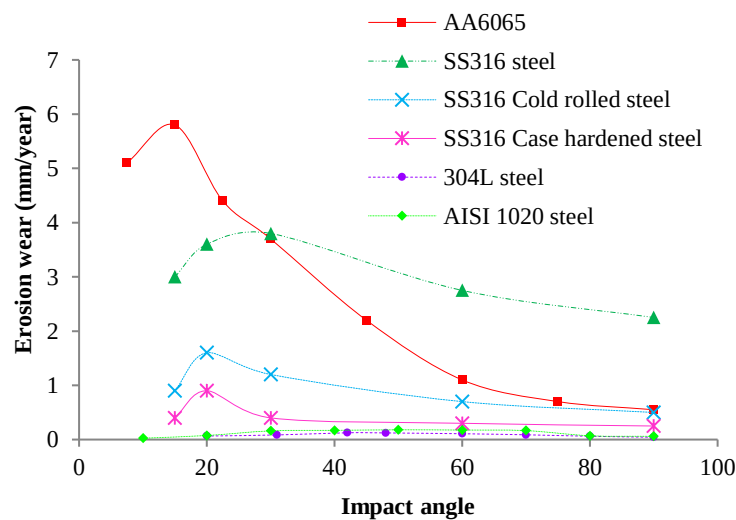


Figure 2.8. Variation in erosion rate with impact angle (Burstein and Sasaki, 2000; Wood et al. 2001; Divakar et al. 2005; Deng et al. 2005; Al-Bukhaiti et al. 2007).

Burstein and Sasaki (2000) determined that as the impact angle varied from range 5 to 22.5° erosion wear of SS304 was increased and after that till 90° it decreased. They also evaluated that AA6063 showed maximum wear at 15° impact angle.

Grewal et al. (2013) studied the influence of parametric variation on the erosion mechanism of CA6NM steel. They used non-recirculating type erosion tester to perform erosion wear experiment. The maintained stand of distance (SOD) between nozzle and sample was around 20 mm. They observed diverse types of erosion mechanism at different impingement angle. The maximum erosion wear observed at impact angle of 30°.

From Figure 2.8, SS316 stainless steel showed highest erosion wear at impact angle of 20° but it minimized when heat treatment processes are experimented on it (Divakar et al. 2005). Researchers (Wood et al. 2001; Deng et al. 2005; Divakar et al. 2005; Desale et al. 2006; Al-Bukhaiti et al. 2007) also found maximum erosion wear occurs of ductile surface within range of impact angle 15 to 45°.

▪ *Erosion wear of brittle materials on the basis of impact angle:*

Brittle materials show different erosion behavior as compared to ductile materials and maximum erosion wear occurs at normal impact angle. Al-Bukhaiti et al. (2007) investigated the effect of impact angle on erosion wear of 1017 steel and high-Cr white cast iron using a slurry whirling-arm test rig. The experiment was performed at different impact angle that ranges from 15 to 90°. They found that erosion wear of both the materials is increases as impact angle was varying from 15 to 45° and afterwards decreases. Erosion wear of high-Cr was found maximum at high impact angle.

Islam et al. (2015) studied the erosion wear performance of 1080 and 1018 steel with the variation in impact angle and velocity of solid. Erosion wear experimentation was carried out with varying impact angle range from 30 to 90° and velocity 36 to 81 m/s. They examined that maximum erosion wear takes place at impact angle 30° and afterwards it decreases. They found that erosion wear of the target materials is a function of impact angle and microstructural properties.

Cai et al. (2015) investigated that erosion wear of brittle materials is increased as the impact angle was changed from 30 to 90°. From literature, it can be concluded that the brittle material showed maximum wear at normal impact angle.

2.2.3 Particulate concentration

Erosion wear of the material is a function of solid concentration of particles (Elkholy, 1983). Erosion wear of the material is affected by concentration as well as setting flux that is created

by slurry particle. Erosion wear of material increases with increase in the solid concentration (Turenne et al. 1989; Burnett et al. 1995; Dasgupta et al. 1998; Prasad et al. 2004; Desale et al. 2006; Desale et al. 2008; Padhy et al. 2009). Relation between the erosion wear performance of target surface and solid concentration can be evaluated by using following correlation:

$$E_w = k(\text{Concentration})^c \quad (2.22)$$

Where E is erosion wear rate, C is solid concentration and K, c are the constant. This equation is helpful to evaluate the rank of dependency on solid-concentration by surface. Grewal et al. (2013) had taken value of n in between 0.9 to 1.3.

Dasgupta et al. (1998) determined the erosion wear investigation on steel specimen with multisize slurry of sand. They found that as the solid concentration was increased from 30% to 50% then the erosion wear rate was decreased.

Gandhi et al. (1999) evaluated the erosion wear of equisize parallel flow under cutting action of slurry particles. They used Zinc as an erodent to evaluate the effect of particle size and velocity with low concentration slurry varied from 0.2 to 0.4. They found that erosion wear rate increased with velocity and solid slurry concentration of brass specimen. Similar trend was also found for CA6NM steel with sand slurry concentration varied from 0.1 to 0.5 (Grewal et al. 2013).

Ramesh et al. (2011) studied the effect of solid liquid concentration on erosion wear of mild steel. They investigated the variation of solid liquid ratio range from 50 to 150 g/l. They found that erosion wear of the mild steel increased with solid concentration and velocity of the solid particle interact on target surface.

Lindgren et al. (2014) studied the effect of solid liquid concentration on erosion wear of 316L, 904L, LDX2101, 2205 and 2507 grade of stainless steel by taking quartz and chromites as solid abrasive. They found that erosion wear is a function of erodent material. Erosion wear of the material decreases with increase in liquid-to-solid ratio.

From above literature, it can be concluded that erosion wear of target surface is dependent on solid concentration of particles. Erosion wear rate increased with increase in solid concentration of equisized as well as multisized slurry.

2.2.4 Material properties

Hardness of the target surface can be defined as how readily it can resist permanent deformation with the impingement of solid particles on it. Hardness factor is the ratio of hardness of the target material to the hardness of the solid eroded particles which can be used to determine the erosion wear. Erosion of the materials is a function of mechanical properties of the target materials as well as solid particles (Gandhi et al. 1998, 2001; Clark and Hartwitch, 2001; Clark and Llewellyn 2001; Deasle et al. 2006; Stack et al. 2008; Szala and Tadeusz, 2015a). The erosion wear phenomenon of ductile and brittle materials is different from each other (referred in Section 2.2.2). From literature, the model for erosion wear of ductile and brittle materials in terms of impact angle is shown in Figure 2.9.

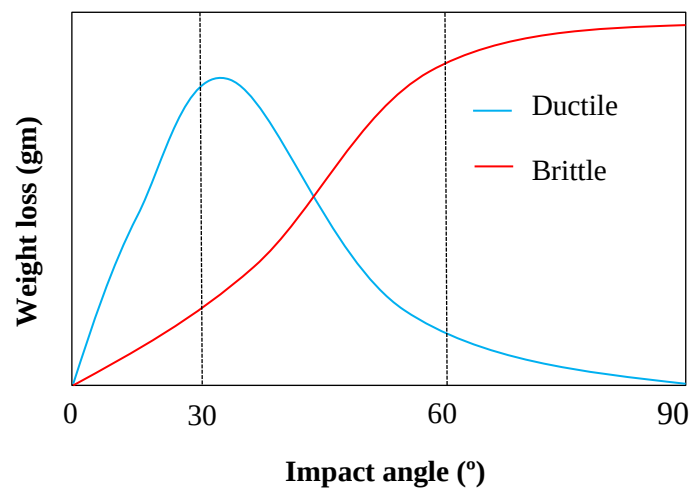


Figure 2.9. Schematic diagram representing erosion wear of ductile and brittle materials.

2.2.5 Particle Size

Particle size is also significantly influence the magnitude of erosion wear rate. Larger size of particles tends toward high kinetic energies. The value of critical size for particles is proportional to fluid flow parameter and surface properties of materials. Erosion wear rate increases with increase in particle size until it reaches the critical value. Tilly (1973) reported that when the particle size was increased above 100 μm , the erosion ratio became constant.

Table 2.3: Analysis of erosion rate with respect to velocity and particle size

S. No.	Materials under erosion	Reason behind erosion	Testing Equipment	Velocity in m/sec	Size Fraction in μm	Erosion in 10^{-6} g/mm^2	Investigators
1.	Casting steel P110	Quartz sand suspensions with oil of flash point: 67 °C	Slurry pot tester	2.4	150-180	8.4±0.2	Clark (1991)
2.	Casting steel P110	Quartz sand suspensions with oil of flash point: 67 °C	Slurry pot tester	2.4	53-18	0.364±0.2	Clark (1991)
3.	Steel N80	Quartz sand suspensions with oil of flash point: 67 °C	Slurry pot tester	9	53-18	0.275±0.1	Clark (1991)
4.	Steel K55	Quartz sand suspensions with oil of flash point: 67 °C	Slurry pot tester	9	53-18	0.25±0.1	Clark (1991)
5.	Hot rolled steel 1020	Quartz sand suspensions with oil of flash point: 67 °C	Slurry pot tester	9	53-18	0.30±0.1	Clark (1991)
6.	Annealed high carbon steel at 900°C for 1h + furnace cooling	30% of coal and 30% of bottom ash	Slurry erosion/ corrosion test rig	5 with sliding distance 10km	Coal: 150-500	15.0±0.2	Modi et al. (2000)
					Bottom ash: 150-300	40.0±0.2	Modi et al. (2000)
7.	Hardened high carbon steel at 900°C for 1h + furnace cooling	30% of coal and 30% of bottom ash	Slurry erosion/ corrosion test rig	5 with sliding distance 10km	Coal: 150-500	2.0±0.1	Modi et al. (2000)
					Bottom ash: 150-300	3.0±0.1	Modi et al. (2000)
8.	Stainless steel-304L	Sand + Tap water	Slurry erosion/ corrosion test rig	3.8 at impact angle 20°	Silica: 400-650	0.65±0.15	Burstein and Sasaki (2000)
9.	Stainless steel-304L	Sand + Tap water+ 0.6M NaCl	Slurry erosion/ corrosion test rig	3.8 at impact angle 20°	Silica: 400-650	0.275±0.15	

10.	Steel-AISI 1020	Sand slurry	Pipeline flow	1.2 at impact angle 20°	Silica: 117	0.075±0.005	Wood et al. (2001)
11.	Aluminium AA6065	I. S. Sand i.e. Silica: 99.3%+Fe ₂ SO ₃ : 0.10%	Slurry Pot tester	3 at impact angle 7.5°	500-600 Avg. size: 550	5.1±0.05	Desale et al. (2005)
12.	Stainless steel-SS 316	Silica sand slurry	Air jet impingement erosion tester	20	100	3.8×10 ⁻³	Divakar et al. (2005)
13.	Stainless steel-SS 316	Silica sand slurry	Air jet impingement erosion tester	26	100	5.2×10 ⁻³	Divakar et al. (2005)
14.	Stainless steel- AISI316	Silica sand slurry	Air jet impingement erosion tester	32	100	6.1×10 ⁻³	Divakar et al. (2005)
15.	Stainless steel-SS 316 + 20% Cold rolled	Silica sand slurry	Air jet impingement erosion tester	20 at impact angle 30°	100	1.2×10 ⁻³	Divakar et al. (2005)
16.	Stainless steel-SS 316 + 12µm case hardening	Silica sand slurry	Air jet impingement erosion tester	20 25–180	100	0.4×10 ⁻³	Divakar et al. (2005)
17.	Brass	Fly ash slurry	Coriolis erosion Wear Test Rig	4.7	25	Appox. 30×10 ⁻³	Chandel et al. (2012)
18.	Brass	Fly ash + bottom ash slurry of ratio 4:1	Coriolis erosion Wear Test Rig	4.7	75	Appox. 54×10 ⁻³	
19.	AA6063	Sand quartz slurry	Slurry Pot tester	3	37.5	0.21	Desale et al. (2009)
20.	AA6063	Sand quartz slurry	Slurry Pot tester	3	550	6.24	
21.	1017 steel	Silica sand slurry	Slurry erosion whirling- arm rig	15 at impact angle 30° for 50 minutes	25–180	7.2	Al-Bukhaiti et al. (2007)
22.	High-Cr white cast iron	Silica sand slurry	Slurry erosion whirling- arm rig	15 at impact angle 30° for 50 minutes	25–180	1.5	

Stack and Pungwiwat (1999) testified that wear rate of material depends on critical size or shape of particle i.e. in between range 106-250 μm . Desale et al. (2009) represented the erosion wear dependency on weighted mean diameter that was discussed in previous studies:

$$E_w = k(d)^b \quad (2.23)$$

Studies of various investigators on different materials with respect to velocity and size fraction with effect of erosion are illustrated in Table 2.3. Small size of particles affects the deformation rate, it was noticed that high deformation rate for small size particle enhanced erosion wear rate.

2.2.6 Particle Shape

Apart from the parameters mentioned above, erosion wear also depends upon the shape of particles. In slurry erosion, particle shape is also one of the major influencing factors for erosion wear. Plastic deformation acts when slurry particles have spherical shape while micro-cutting and brittle fragmentation is established in case of angular shape. Bouwman et al. (2004) suggested a relationship which has been developed by Riley (1941) for the calculation of the shape factor (SF) of erodent particles, as expressed below:

$$SF = \frac{4\pi A}{p^2} \quad (2.24)$$

Levy and Chik (1983) found that angular particles causes high wear rate as compared to spherical particles as given below:

$$\text{Wear caused by angular particles} \approx 4 \times (\text{wear caused by spherical particles}) \quad (2.25)$$

Particle shape had determined as particle shape factor equations or models proposed by various researchers. Spherical particles have high shape factor than the angular particle. Erosion wear mechanism of target surface was shifted with nature of erodent such as its hardness and shape factor (Desale et al. 2009; Hawthorne et al. 2002; Rajahram et al. 2011; Lindgren et al. 2014).

Clark and Hartwitch (2001) studied the effect of particle size on erosion wear of AISI 1020 and AISI 1045 steel. Erosion wear investigation was carried out using silica sand as erodent material. They found that erosion wear of materials increases as size of eroded materials increases

Bahadur and Badruddin (1990) performed an experimental study to investigate the effect of particle size and shape on erosion wear at high jet velocities. They used a jet tester having a velocity varying from 40 to 65 m/s to perform the experimentation. They used three different erosion agents (SiC, Al₂O₃, and quartz) with particle sizes of 10 to 500 µm. They found that the circularity factor of these particles lies between 0.70-0.97. Additionally, Heilbronner and Keulen (2006) performed a study on shape analysis of fault rocks by investigating the size and shape of grains. They had reported a correlation to analyze the roundness of particles which is given below;

$$RD = \frac{4 \times A_p}{\pi \times D_{maxfret}^2} \quad (2.26)$$

where $D_{maxfret}$ represents the characteristically faulted rectangular particles. This factor gives the measure of long-axis. They also discussed the Paris factor for analysis of grain shapes, as written below:

$$PF = 2 \left(\frac{P_p - P_{ch}}{P_{ch_A}} \right) \quad (2.27)$$

Desale et al. (2006) modified the shape factor given by Riley (1941) to evaluate the circularity of eroding agents, as given below:

$$SF = (SF_{Avg} SF_{Max} SF_{Min})^{1/3} \quad (2.28)$$

They investigated the effect of erodent particles on erosion wear of AA6063 and AISI 304L. Erosion wear performance of both ductile materials was examined by using quartz, silicon carbides and alumina taken as erodent of same size with velocity of 3 m/s of solid particle. They found that erosion wear of the material increases with decrease in shape factor of erodent.

Woldman et al. (2012) performed a wear analysis experimentation using a dry sand rubber wheel. They found that the size of sand particles lies in the range of 80 to 500 μm . They have also found that the (CF) of sand lies in the range of 0.56 to 0.65.

Thakur et al. (2011) investigated the effect of solid concentration on erosion wear of SS-304 steel. Erosion wear investigation was conducted at a velocity of 0.5 m/s with solid concentration ranging from 10, 20 and 30%. Erosion wear of the material increases with increase in the solid concentration of silica oxide solid particle. They also found that erosion wear of material is a function of surface property.

Walker and Humbe (2015) examined the effect of particle shape and size on erosion wear of white cast iron. Erosion wear experiment was performed on large scale Coriolis tester by using SiC, sand and alumina as eroded material. They developed correlation for the prediction of the effect of particle shape on erosion wear. They found that shape of the erodent shows dominating effect on erosion wear of white cast iron at different velocity and impact angles. Walker and Humbe (2015) analyzed the effect of particle shape on the erosion wear of white cast iron. They used a Coriolis tester to perform the wear experiments. They computed the (CF) of sand, alumina, and SiC to be 0.73, 0.71, and 0.64, respectively.

Literature also indicates that very few researchers have performed the erosion wear studies on the basis of particle shape. The shape of particles majorly contributes in erosion wear mechanism. Spherical shaped particles resulted in plastic deformations and microcutting action which is due to rebounding nature of spherical particles with target surface of workpiece. Irregularly shaped blocky particles generate the ploughing and smooth craters (Walker and Humbe, 2015). Angular shaped particles generate the cracks and craters and during this process, chipping of erodent particles takes place (Desale et al. 2006). It can be said that the shape factor can play an important role in analysis of erosion wear.

2.3 DESIGN AND DEVELOPMENT OF THERMAL SPRAYING PROCESSES

Thermal spray coating is basically a term used for number of coating techniques employed on nonmetallic and metallic coatings. It is categorized into main three group according energy sources: electric arc, plasma arc spray and flame spray. In this process coating can be

deposited using powder, rod or wire for required application. Materials used for coating are summarized in Table 2.4.

Table 2.4: Materials used for coating

S. No.	Type /phase	Materials
1	Single- Phase	Alloys, polymer, ceramics and intermetallic
2	Composite	WC, Co, Cr, Ni, Ti and Al-based
3	Layered	FGMs (Functionally Gradient Materials)

Various thermal spraying like flame spraying, arc spraying, atmospheric plasma spraying, vacuum plasma spraying, detonation gun spraying, high velocity oxy-fuel spraying, laser spraying etc. are used in different industries. Brief details about different thermal spraying processes are discussed below:

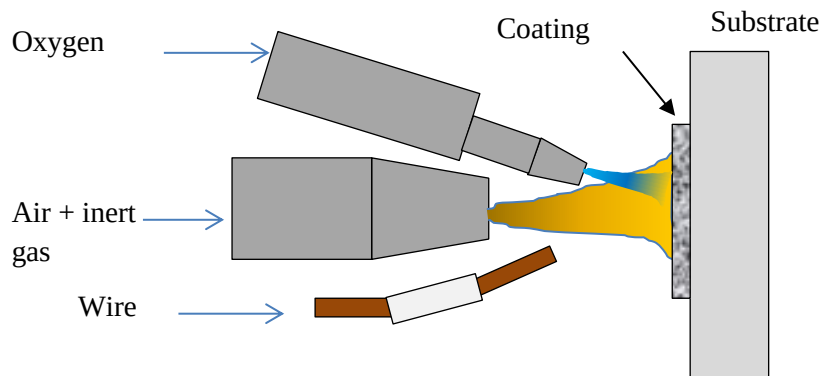


Figure 2.10. Schematic diagram of flame spraying process (Weman, 2012).

2.3.1 *Flame spraying process*

Flame spray is the coating process in which the metal powder or combustible wire is melted by a combustion flame. In flame spray process, oxygen, fuel gases or inert gases are used as carrier gas (Weman, 2012). Most commonly used fuel gases are acetylene, propane and hydrogen. During the process, a combustion flame is passed through convergent, divergent or parallel section nozzles to perform the coating. Usually, flame is a stream of compressed air and inert gas. The process parameters used to perform the flame spray process are summarized in Table 2.5. The range of different properties achieved by flame spray process is listed in Table 2.5. A schematic diagram of flame spraying process is shown in Figure 2.10.

Table 2.5: Properties achieved by different coating processes (Steffens et al. 1994; Pawlowski, 1995)

Properties	Values				
	Flame spray	Arc spray	Atmospheric plasma spray	Detonation Gun spray	HVOF spray
Porosity (%)	10-20	10-20	1-7	0.5-5.0	~1%
Bond strength (MPa)	15-30	---	---	>70	>40
Thickness (μm)	100-2500	100-1500	50-500	~300	----

2.3.2 Arc spraying process

Arc spraying is the coating process in which the combustible wires are subjected to compressed gas and propelled to substrate material. In this process, two wire spools of electronically conductive materials (like metals or alloys) are drawn to deposit them on substrate in form of liquid droplets by utilizing the arc heating. A schematic diagram of flame spraying process is shown in Figure 2.11. The velocities of molten particles reach up to 150 m/s. The range of different properties achieved by flame spray process is listed in Table 1.3. In industrial sector, two most commonly used arc spraying processes are atmospheric plasma spraying and vacuum plasma spraying process (Steffens et al. 1994; Weman, 2012; Andrej et al. 2017).

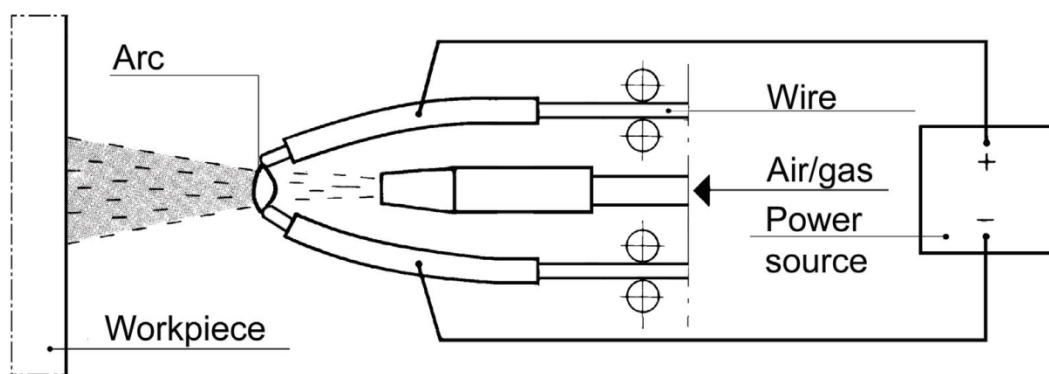


Figure 2.11. Schematic diagram of arc spraying process [Weman, 2012, Electronic and printing permission of ©Elsevier].

2.3.3 Atmospheric plasma spraying process

A schematic diagram of atmospheric plasma arc spraying process is shown in Figure 2.12. An atmospheric arc spraying unit consists of an anode (Cu) and cathode (W). Argon (Ar) or mixture of argon with other gases (like He, H₂, N₂) is used as carrier gas. During the process, the carrier gas is heated up the electric arc discharge and generates a plasma arc to melt the combustible wires. The velocities of molten particles reach up to 800 m/s (Pawlowski, 1995; Sayed, 2004). The temperature of plasma remains very high i.e. about 14000 K. The range of different properties achieved by flame spray process is listed in Table 2.5. The materials like nitrides, carbides, Ti, Ta which are sensitive to combustion process can be sprayed by using atmospheric plasma spraying process.

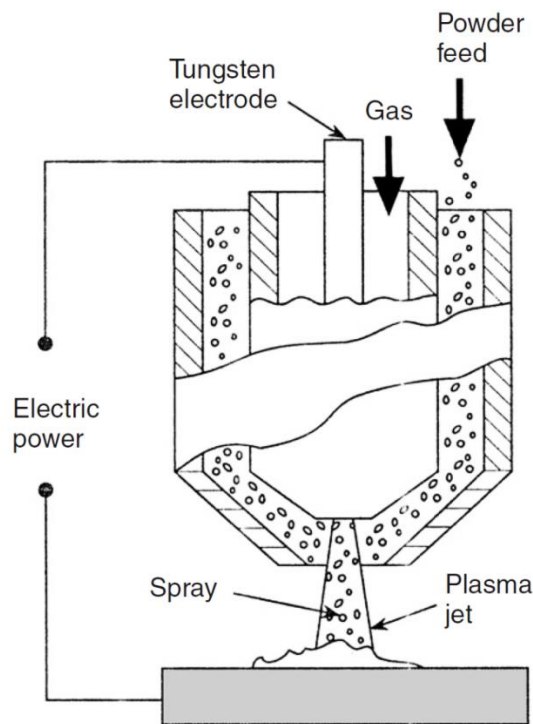


Figure 2.12. Schematic diagram of atmospheric plasma arc spraying process [Blunt and Balchin, 2002, Electronic and printing permission of ©Elsevier].

2.3.4 Vacuum plasma spraying process

This process is also known as low-pressure plasma spraying process. A schematic diagram of vacuum arc spraying process is shown in Figure 2.13. This process is performed at low pressure by using a plasma torch having a vacuum nozzle.

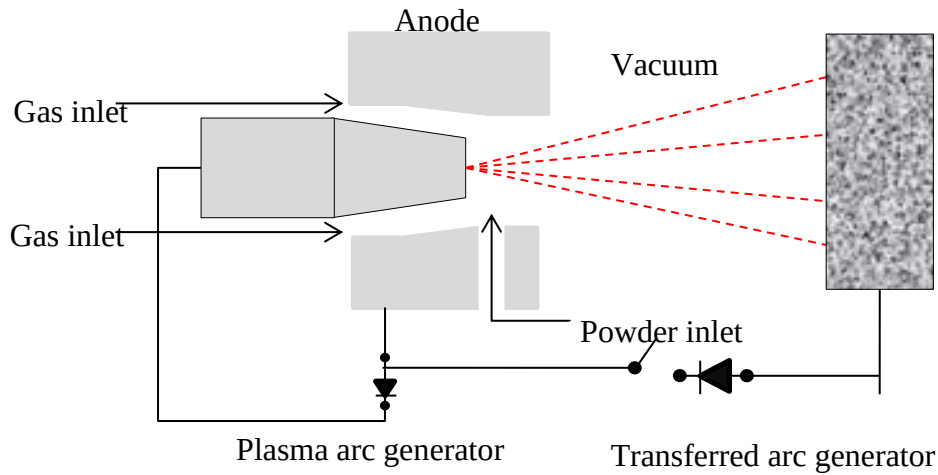


Figure 2.13. Schematic diagram of vacuum plasma arc spraying process.

2.3.5 Detonation gun spraying process

Detonation gun spraying is the coating process in which a metal powder is deposited by detonation wave. The detonation wave helps to generate a spark by raising the pressure of mixture (oxygen, fuel gas and metal/non-metallic powder) and heats up then accelerates the powder particles above its melting point. Usually, Argon (Ar) is used as a fuel gas. The velocities of molten particles reach up to 750 m/s by using D-GunTM and 1000 m/s by using Super DGunTM (Irving et al., 1993, Tucker and Ashary, 1995). After the process, the barrel is cleaned with nitrogen gas. Detonation process is a repetated i.e. 1–15 times/second (Berget, 1998). The range of different properties achieved by detonation gun spray process is listed in Table 2.5. A schematic diagram of detonation gun spraying process is shown in Figure 2.14.

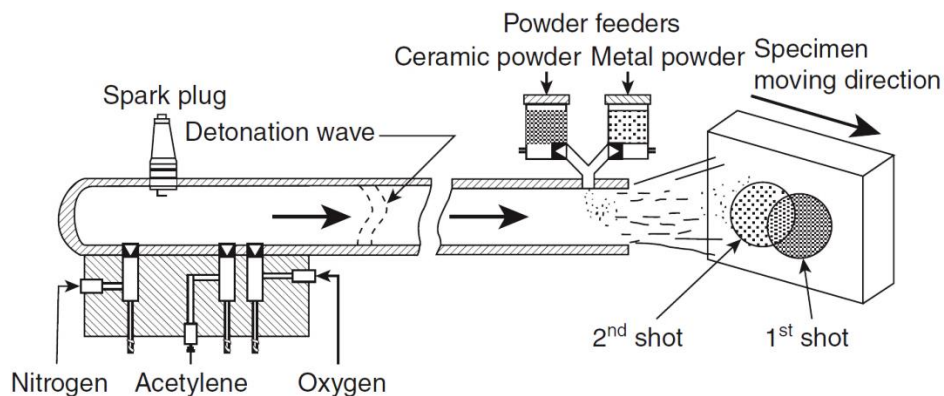


Figure 2.14. Schematic diagram of D-Gun spraying process [Electronic and printing permission of ©Elsevier] (Kim et al. 2003, Ke et al. 2011).

2.3.6 Laser spraying process

The laser spraying process is entirely different from the above mentioned processes. The above mentioned processes are either using electrical energy or chemical energy to deposit the metallic or nonmetallic powders. However, the laser spraying is the entirely different process in which laser beams are used to melt the injected particles. The laser spraying system generates a 10 kW CO₂ optical energy laser beam which is sufficient to melt the powder particles which are injected through a designed feeder. The diameter of laser beam is usually kept parallel to the sprayed surface in range of 2-3 mm (Pawlowski, 1995). A schematic diagram of laser spraying process is shown in Figure 2.15. At present time, the laser cladding the most widely used inversion of laser spraying process.

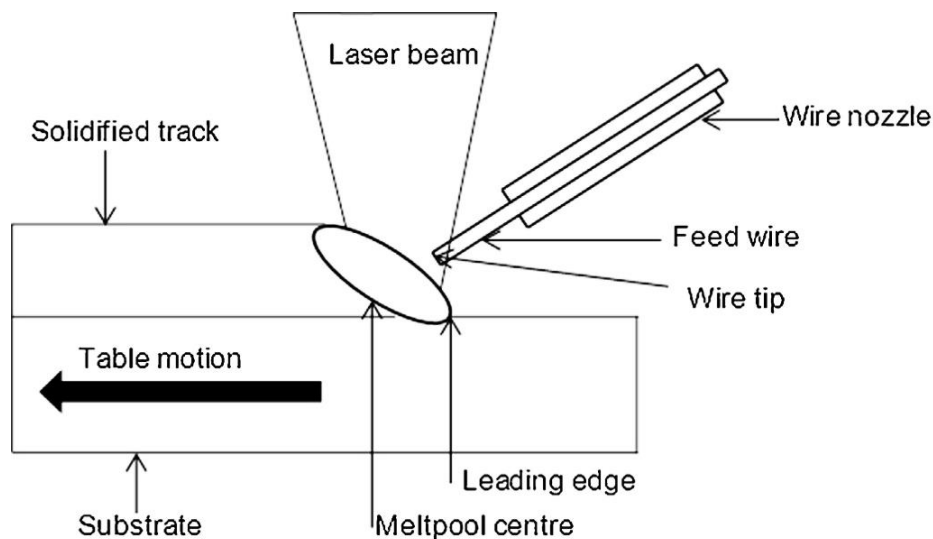


Figure 2.15. Schematic diagram of laser spraying process [Electronic and printing permission of ©Elsevier] (Abioye et al. 2013).

2.3.7 Underwater spraying process

A schematic diagram of underwater spraying process is shown in Figure 2.16. Underwater spraying process was developed from a point-of-view of protecting the underwater equipment and offshore structures (Ohliger et al., 1990). A Jet-Kote-system was developed firstly to deposit the protective coatings on the offshore structures. Under-water plasma spraying is process in which the substrate is free from dust, noise and radiation.

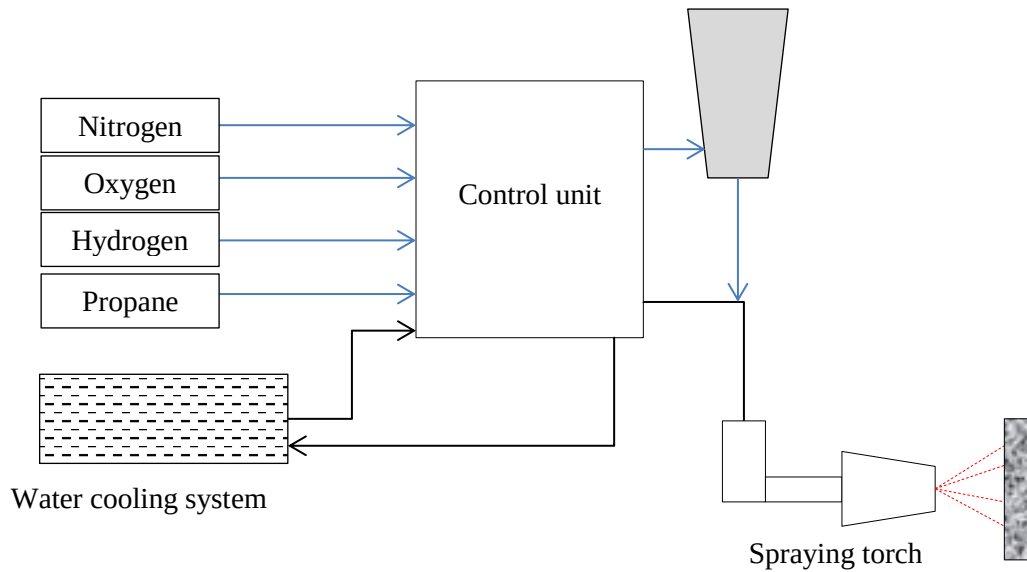


Figure 2.16. Schematic diagram of underwater spraying process.

2.3.8 High velocity oxy-fuel spraying process

High velocity oxy-fuel (HVOF) spraying process is the coating process in which powder particles injected at a very high velocity and kinetic energy. The HVOF spraying unit consists of a torch from which compressed air, carrier gas (nitrogen mixed with powder) and fuel gases passes to serve the coating deposition. A schematic diagram of HVOF spraying process is shown in Figure 2.17. The range of different properties achieved by HVOF spray process is listed in Table 2.5.

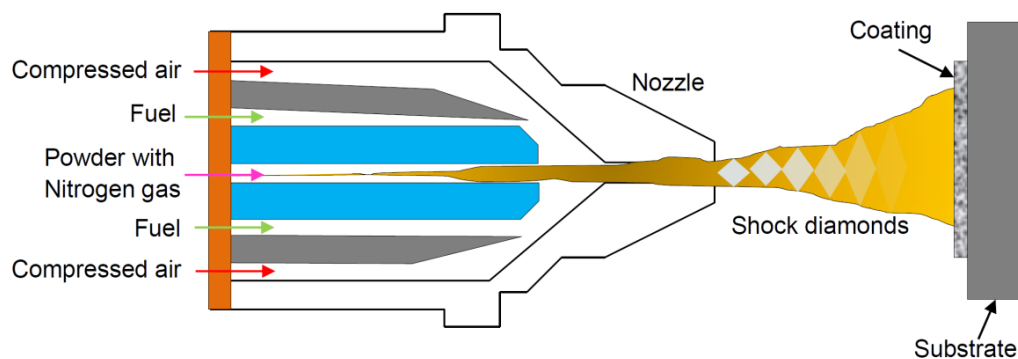


Figure 2.17. Schematic diagram of HVOF spray gun.

The working principle of HVOF process is the high kinetic energy of particles with substrate. HVOF comprises a fuel gas (such as acetylene (C_2H_2), hydrogen (H_2), kerosene, propane

(C_3H_8), propylene (C_3H_6)) which burns with oxygen according to the desired coating requirement. These gases are injected at a very high pressure which tends to form a high velocity jet (Berjet, 1998; Parker and Kutner, 1991). The coating powder is injected into the stream or jet in axial direction parallel to jet. The mixture of gases is burnt in the combustion chamber and flow through the divergent section (i.e. nozzle). The combustion chamber and nozzle is cooled down by air or water medium. During the process, the temperature of gases becomes extremely high i.e. greater than $2760^{\circ}C$ (Parker and Kutner, 1991). The gas moves at higher velocity as compared to the injected powder particles (Thorpe and Thorpe, 1993).

The evolution of HVOF guns was started from early 1980's. HVOF spraying process is known for its versatility. Pure metals as well as ceramics/cermets can be sprayed by using the HVOF process. The pure metals (like Al, Cu, Mo, Ni, Ti, etc.), metallic alloys (like steel, brass, ferrites), ceramics (like Al_2O_3 , Cr_2O_3 , Mo_2C , ZrO_2 , Y_2O_3), cermets (like WC/Co, WC/Co/Cr, NiCrSiBC, NiCrSi, $Cr_3C_2/NiCr$ etc.), and other compounds (thermoplastics, graphite, metallic + cermics, metallic + nonmetallic, carbon nanotubes etc.) can be sprayed by using HVOF process (Kumar and Modi, 1995; McIntyre, 1996). The development in HVOF process remained rapid till the 1995. During this period, few of the modifications were done in HVOF process which are hypersonic velocity impact fusion (HVIF) and High-velocity-air fuel (HVOF) process. HVIF process was developed by Browning (1992). This process is also works on the same principle as HVOF but the static temperature of particles is kept below their melting point to avoid softening of the smallest particles. HVOF process was developed by Irving et al. (1993) (introduced by Browning Thermal Systems Inc.). In this process, air is used instead of oxygen.

2.4 EROSION WEAR OF WC-Co-Cr CERMET COATINGS

This overview is carried out with an objective for providing inclusive literature review about erosion wear of WC-based coatings. Investigators have made efforts to find the erosion wear by carrying out lab scale and pilot plant test loops. The comprehensive literature survey on erosion wear of WC-based coatings is discussed below:

Wheeler and Wood (2005) performed an experimental study to analyze the erosion wear of AISI 1020 steel coated with 86WC–10Co–4Cr powder. They carried out the laboratory scale experiments on a slurry jet erosion tester with sand slurry. Results showed

that erosion resistance of diatec HVOF 86WC–10Co–4Cr coating was twice than d-gun HVOF coated specimen.

Mann et al. (2006) studied erosion wear of X20Cr13, 17Cr–4Ni pH steels and Ti6Al4V titanium alloy coated with WC–10Co–4Cr, Stellite 6 and 12 powders using HVOF coating. They found that TiAlN PVD coated with WC–10Co–4Cr powder showed better tribological characteristics as compared to other.

Maiti et al. (2007) studied the erosion wear performance of AISI 304 stainless steel with WC based HVOF coatings. They had prepared the different composition of coating powders by adding 0, 10, 20 and 30% of WC powder in WC–9Co–5Cr. They found that the hardness of WC–9Co–5Cr was increased 26% with the addition of 20% WC powder.

Cho et al. (2008) have studied the microstructure of HVOF sprayed nano and micron WC–Co coating powders. The particle size of sprayed nano and micron powder was taken in range 0.1–1 μm and 1–40 μm respectively. The nano and micron coating powders were taken in proportion of 12 and 88% (by weight) respectively. Carbon steel was taken as a substrate material. They found that coating hardness is strongly dependent on spray parameters and powder size. Hardness of nano WC–Co was lower than that of micro WC–Co because of hard WC decomposition as compared to less hard W_2C , W and graphite. Porosity of micro WC–Co coating was found smaller than that of Nano WC–Co because of less evolution of unwanted carbon oxide gasses through micro WC–Co coating.

Lee et al. (2010) performed the erosion wear experimentation on S45C steel coated with WC–10Co–4Cr using HVOF technique. They used a pin-on-disk wear tester to perform erosion wear experiments at ambient temperature. It was concluded that the fracture toughness and wear resistance of base material improved after depositing multiparticulate coating powder due to formation of low porosity layers.

Thakur et al. (2011) reported that the slurry erosion behavior of coated surface with the help of slurry pot erosion tester. They performed erosion wear testing with varying size of erodent particle and concentration. They found that fine grains of WC in WC–CoCr cermet coating powder provided higher erosion resistance as compared to conventional cermet coating at all testing parameter.

Grewal et al. (2013) studied the influence of parametric variation on the erosion mechanism of CA6NM steel coated with WC and Ni-based cermet coatings. They used non-recirculating type erosion tester to perform erosion wear experiment. The maintained Stand

of distance (SOD) between nozzle and sample was around 20 mm. They noticed at low velocity erosion rate is inversely proportional to soil concentration whereas at higher concentration velocity show linear relationship with solid concentration of erodent. They also reported that velocity is dominating factor for erosion wear.

Vite-Torres et al. (2013) analyzed the erosion performance of AISI 420 stainless steel. They used silicon carbide (angular shaped) and round grit particles (spherical shaped) as an erodent material. Jet impingement tester was used for conducting experiment. The particle size of erodent was varied from 400 to 420 μm with impact angle varying from 30° to 90° with an interval of 15° at constant velocity 24 m/s. They found that shape of erodent impact on erosion wear rate. Wear scar was observed to be elliptical at 30° and circular at 60° . The maximum erosion occurs at 30° impact angle which confirms that the material is exhibiting ductile behavior.

Murugan et al. (2014) have studied the different parameters of WC-10Co-4Cr HVOF coating on naval brass substrate. They studied the effect of different parameters like spray distance, powder feed rate and flow rate. The statistical tools such as response surface methodology, analysis of variance and design of experiments were also used to attain the required optimal hardness and porosity. They found that spray distance had least influence on the coating hardness and porosity values and followed by powder feed rate, LPG flow rate and oxygen flow rate.

Kumar et al. (2016) studied the erosion wear of WC-10Co-4Cr HVOF coated 23-8-N Nitronic steel. They used 23-8-N Nitronic steel as substrate material which was treated by chemical solution ($1220^\circ\text{C}/150\text{min}$). Erosion resistance of coatings was evaluated by air jet erosion tester on two different impact angles (30° and 90°). They found that coating on solution treated substrate was superior to cast substrate. They also found that erosion response of WC-10Co-4Cr coating also depends on the relative size of the impact crater with respect to the WC grain size.

Many researchers have used WC-based coatings to improve the erosion wear resistance of stainless steels. WC-10Co-4Cr is very widely-used in many industrial applications (Wheeler and Wood, 2005; Maiti et al. 2007; Lee et al. 2010, Hong et al. 2013). A good deal of literature is available on WC-Co-Cr coatings deposited by different spraying processes.

2.5 EROSION WEAR OF METAL COMPOSITE COATINGS

This overview is carried out with an objective for providing inclusive literature review about erosion wear of different metal composite coatings such as Stellite, Colmonoy, Ni-based, Al-based composites. The comprehensive literature survey on erosion wear of metal composite coatings is discussed below:

In initial years, Chattopadhyay (1993) performed an investigation on the erosion wear of Stellite-6 by successfully depositing it on CA6NM via a plasma-welded overlay.

Shrestha et al. (2005) performed a study on erosion-corrosion analysis of Ni-Cr-Mo-Si-B coating deposited by HVOF process. They found that Ni-Cr-Mo-Si-B coating showed significant results against erosion-corrosion environment.

Tam et al. (2002) studied the cavitation erosion of Ni-Cr-Fe-WC coating laser cladded on brass material. They reported that erosion resistance of brass was increased about 9.1 times with Ni-Cr-Fe-WC coating.

Yarrareddy et al. (2006) presented a study on the slurry erosion behavior of Stellite-6 and Colmonoy-88 coatings that were deposited on cast iron using a laser cladding process. They reported that both powders contain high amounts of Cr, WB, and WC, all of which provide high resistance to erosion, abrasion, and corrosion. They mentioned that future studies could be done on hard-facing alloys in the hydraulic machinery industry. Arji et al. (2007) had performed an experimental study on erosion wear of Stellite-6 by using the sand as an erodent.

Sidhu et al. (2007) investigated the erosion behaviour of GrAl steel with NiCr and Stellite-6 powder using HVOF coating. They performed the erosion wear experimentation on air jet erosion tester. It was found that Stellite-6 coated GrAl steel show higher erosion resistance than NiCr.

Shivamurthy et al. (2007, 2009) performed a study on the cavitation erosion wear of 13Cr-4Ni steel coated with Stellite-6 and Colmonoy-88 powders. They used laser surface alloying (LSA), which is a two-stage process for applying deposits onto 13Cr-4Ni steel. The results indicate that depositing Stellite-6 resulted in a 1.5- to 2-fold improvement in surface hardness for 13Cr-4Ni steel, and a 2-fold improvement in surface hardness was found when Colmonoy-88 powder was deposited on the steel.

Arji et al. (2009) performed an experimental study to investigate erosive wear of Ni-Cr-Si-B coating flame sprayed on mild steel. They used sand slurry having concentration

range of 20-40% at different rotational speeds namely 600, 800 and 1,000 rev/min. They found that Ni-Cr-Si-B had improved the wear of mild steel substrate.

Hong et al. (2013) performed erosion wear experimentation on 13Cr4Ni steel coated with Cr_2O_3 -NiCr powder using HVOF coating. They observed that micro hardness of base material improved due to presence of Cr_2O_3 , Cr_7O_3 and (Cr, Ni) phases in coating.

Goyal et al. (2012) studied the erosive wear of Cr_3C_2 -NiCr coated ASTM A743 steel at different particle sizes. They used erodent of 100 and 300 μm particle size. They noticed the rebounding of impact particles from the target surface resulted in less value of exponent. They value of velocity exponent was observed to be 1.40 and 1.2 for the uncoated and coated CA6NM steel respectively. They also found that uncoated steel exhibited ductile behavior (includes microcutting, plastic deformation and plowing) while coated steel exhibited brittle mode of fracture (includes microchipping and localized chip formation).

Yao (2014) studied the surface tribology of Ni-based (NiCrBSi-WC(Co)) coating. Results show that 50% addition of WC(Co) content significantly improved the wear performance of NiCrBSi coating.

Karimi et al. (2016) studied the porosity of Ni-based (NiCrBSi) flame sprayed coatings. They reported that porosity of this coating was improved in range 11.7-1.9% after going through remelting process. Aubry et al. (2016) reported the various mechanical properties of Stellite and Colmonoy coatings deposited by cladding process.

Li et al. (2017) studied the corrosion of Ni based (NiCrBSiFeCoC) coating. They also studied that coating possesses carbides phases namely Cr_{23}C_6 , Cr_7C_3 and WC which contributes in high microhardness.

Gnanasekaran et al. (2017) investigated the mechanical and tribological properties of Colmonoy-5 coating deposited on 316 LN steel. They performed a laser hardfacing to deposit the Colmonoy-5 coating on 316 LN. They found that wear resistance of 316LN steel was improved by 20 times with deposition of Colmonoy-5.

From literature survey, it can be said that Ni- and Co-based coatings were found to be promising in tribological applications (Hong et al. 2013; Szala et al. 2013, Szala et al. 2014; Karimi et al. 2016). Stellite is suggested by several researchers for high-erosion-duty conditions in hydraulic machinery. Ni- and Cr-based coatings are able to withstand against erosion wear in mining conditions (Szala and Tadeusz, 2015a, 2015b).

2.6 GAPS IN RESEARCH

The literature review conducted in above section revealed many hidden layers of gaps in terms of slurry pump performance. Following gaps of knowledge are observed in performance characteristics of the slurry pump:

- i. Erosion wear studies have also been limited for equisized particles. In general, majority of commercial applications pumps slurry under heterogeneous conditions with wide particle size distribution. No systematic attempt has been made to investigate wear characteristics for multi-sized commercial slurries.
- ii. Data generated by different test rigs show large variations due to difficulties in controlling various parameters responsible for erosion wear.
- iii. The empirical correlations developed experimentally for prediction of erosion wear are applicable for particular slurry and cannot predict reasonable with other slurries.
- iv. The erosion wear studies for the flow of coal-ash slurries were not widely seen in available literature.
- v. In previous studies, a great interest in analysis of erosion wear has done by varying the process parameters. Very few researchers have performed the erosion wear studies on the basis of particle shape. From above literature, it can be concluded that the shape factor can play an important role in analysis of erosion wear.
- vi. Some of the surface modification techniques are promising for improving the surface resistance to wear. Feedstock powders still require further modification in coating to withstand different type of slurries and conditions.

2.7 PROBLEM STATEMENT

In previous sections, a comprehensive literature review was conducted from which gaps in the present field of erosion wear study were revealed. In this context, the present study was conducted to evaluate the erosion wear of different pumping materials and coatings by using different slurries. In present investigation, three different slurries namely fly ash, bottom ash and sand were used. Four different pumping materials namely grey cast iron, stainless steel SS304, SS316L and super duplex stainless steel SDSS2507 were used. High-velocity oxy-fuel (HVOF) process was used to spray the different coating powders on pump materials. In present investigation, the coating powders used was Ni-20Cr₂O₃, Ni-20Al₂O₃, Al-20TiO₂,

Stellite-6 and Colmonoy-88. The WC-10Co-4Cr cermet powder was modified by addition of small proportion of Y_2O_3 , Mo_2C and ZrO_2 powders.

2.8 OBJECTIVES OF PRESENT STUDY

The limitations of available experimental data and correlations have motivated the author to undertake the present study. The efforts of the present study will be to:

- i. Investigate the physical and chemical characteristics of slurry suspension like fly ash, bottom ash and sand at different solid concentrations.
- ii. Investigate the effect of various parameters namely flow velocity, solid concentration, particle size and properties of materials on erosion wear characteristics of different pumping materials.
- iii. Investigate the slurry erosion behavior of coated pumping materials with different powders combination.
- iv. Optimize the influencing parameters on slurry erosion for different pumping materials and coatings using optimization tool.

2.9 EXPERIMENTAL METHODOLOGY

In previous sections, the motivation and objectives of present work was highlighted. To achieve these objectives, different facts have been identified which are given in some detail in this chapter. Various equipment, methods, techniques and procedures were employed to achieve the objectives of present work. The methodology behind the present study has been explained in flow chart represented by Figure 2.18. The research methodology adopted in present study has been explained in Figure 2.18 (also disused in Section 1.4, Chapter 1). The parts of research methodology in present study are the selection of materials and selection of equipment, procedures, methods and techniques.

2.10 RESULTS ORIENTATION

Results from different experiments were plotted by using different mathematic tools like Microsoft Excel, Matlab, ImageJ, Minitab etc. The use of software tools is written below:

- The graphical representation of different terms was done by using Microsoft Excel 2010.
- Minitab 18.0 was used to apply the design of experiments techniques.

- MATLAB 16.0 was used to plot various surface plots and applying the artificial neural network.
- ImageJ software package was used to perform the various shape analysis techniques and to plot 3D profiles and measurements from SEM images.

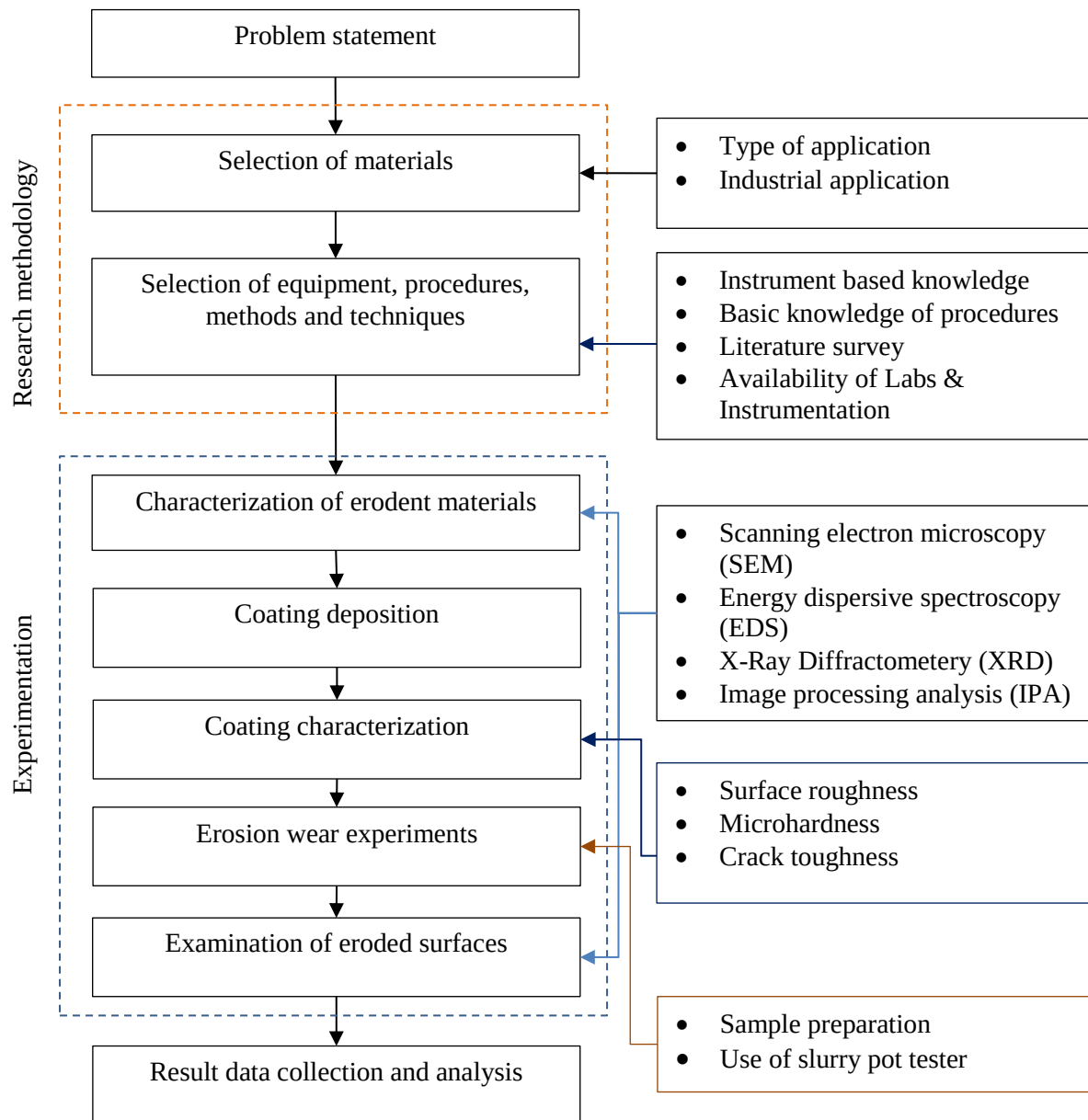


Figure 2.18. Flow chart for experimental methodology.

CHAPTER 3

CHARACTERIZATION OF ERODENT MATERIALS

CHAPTER 3

CHARACTERIZATION OF ERODENT MATERIALS

Different types of slurries are processed through slurry pumps in mining industries and thermal power plants. Sand/silt is processed through the slurry pumps in mining and marine industries. Thermal power plants produce fly and bottom ash are produced after coal combustion products which are disposed to dyke area by using single or multistage centrifugal slurry pumps. Three of these erodent materials are dangerous for life of slurry pump. The protection of slurry pumps in the thermal power plants and mining industries is a major challenge.

In previous chapter, the details about collection of erodent samples and instrumentation to characterize the erodent materials were discussed. The literature overview carried out at initial phase of present investigation has revealed that erosion wear of different materials depends upon the various properties of erodent materials. In this context, it is necessary to study the different properties of physical, chemical and mineralogical characteristics of erodent particles and slurry.

In this chapter, an investigation is carried out to examine the different properties of erodent materials. This chapter covers analysis of various properties of erodent materials such as surface morphology, chemical composition, distribution, particle size/shape, porosity, static settled concentration, specific gravity, bulk density, pH value, and crystalline structure.

3.1 COLLECTION OF ERODENT SAMPLES

In present study, the three different materials namely fly ash, bottom ash and sand have been used to perform the erosion wear experimentation. Sand silt samples were collected from the northern India. The source of sand silt samples was Nathpa Jhakri Dam, Kinnaur, Himachal Pradesh (India). Geographic location of Nathpa Jhakri Dam has been shown in Figure 3.1.

Bottom ash sample was collected from dyke area of GGSS Thermal Power Plant Ropar, Punjab (India). Geographic location of GGSS Thermal Power Plant, Ropar, Punjab (India) has been shown in Figure 3.2. However, fly ash sample was collected from electrostatic precipitators of GGSS Thermal Power Plant Ropar, Punjab (India). Geographic location of electrostatic precipitators of GGSS Thermal Power Plant, Ropar, Punjab (India) has been shown in Figure 3.3.



Figure 3.1. Location of samples of sand silt (Nathpa Jhakri Dam, Himachal Pradesh, India) [©Google Earth, 2018].



Figure 3.2. Location of samples of bottom ash samples (GGSS Thermal Power Plant Rupnagar, Punjab, India) [©Google Earth, 2018].

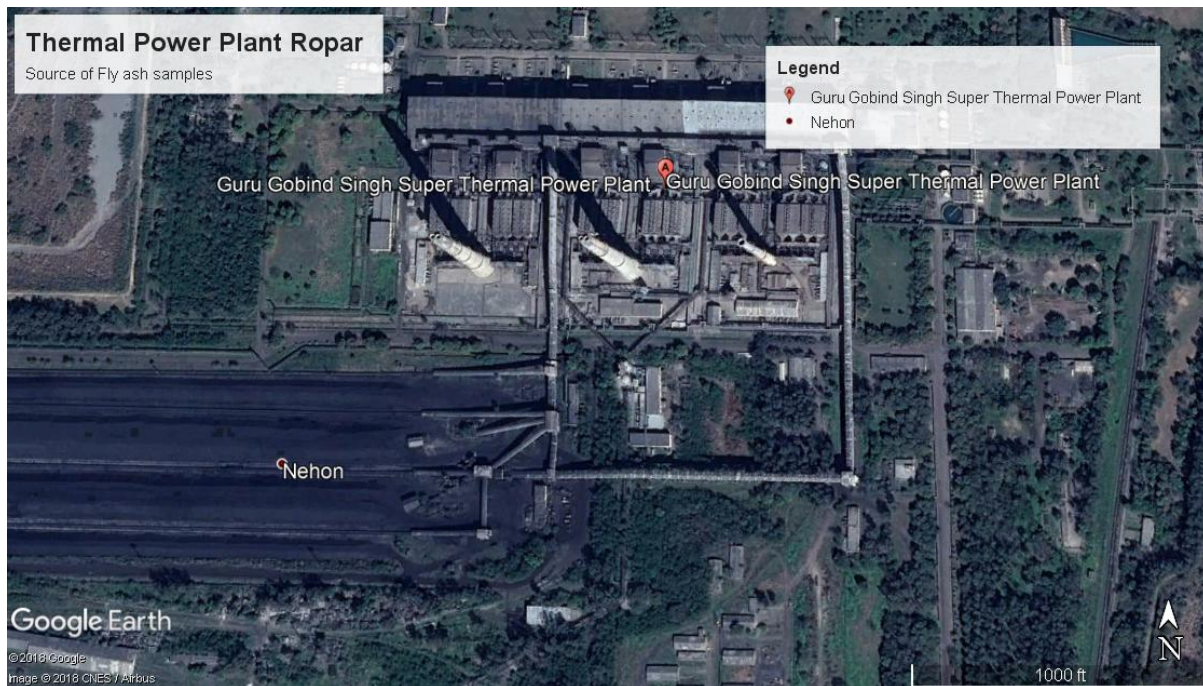


Figure 3.3. Location of samples of fly ash samples (GGSS Thermal Power Plant, Rupnagar, Punjab, India) [©Google Earth, 2018].

3.2 MICROSTRUCTURE, CHEMICAL COMPOSITION AND CRYSTALLINE PHASE CHARACTERIZATION

Characterization of erodent materials is also important part of erosion wear assessment. Various equipment/techniques/methods were employed to analyze the shape, surface microstructure, crystalline phases and chemical composition of erodent, coated and eroded samples. In present work, the surface examination techniques namely scanning electron microscopy (SEM), energy dispersive spectroscopy (EDS) and X-ray Diffractometry (XRD) were used which has been discussed in details as follows.

3.2.1 Morphological analysis

Morphological analysis is carried out to analyze the surface microstructure of erodent particles. In present investigation, the morphological analysis was carried out by using a Scanning electron microscope (manufactured by JEOL, Netherlands, Model: JSM 6510LV) at Sophisticated Analytical Instruments (SAI) Laboratories, Patiala, India. The working principle of scanning electron microscopy is explained follows.

Preparation of samples

Fly ash, bottom ash and sand were dried separately in microwave oven for removal of wetness present in samples. Microwave oven used in the present study was manufactured by Sentwin Ltd., India used in present study. The JEOL, JSM 6510LV scanning electron microscope requires a gold coated sample for SEM-EDS analysis. The gold coating was performed on materials with the help of auto fine coater manufactured by JEOL, Netherlands (Model: JFC-1600) which facilitates the conduction behavior to insulated erodent particles. Afterwards they placed in sample holder which is mounted in SEM machine. The sample holders used in SEM machine are shown in Figure 3.4.



Figure 3.4. (a & b) Multiple sample and (c) single sample holder for SEM of powdered samples.

Working Principle

Initially, the coated powder samples of small quantity (few mg) are placed in sample holder are mounted in a high vacuum (about 2×10^{-6} torr) chamber of SEM machine. A tungsten filament electron gun is used to generate a fine beam of electron ($\sim \phi 10$ nm) which requires 20 kV accelerating voltage. The electron beams generated from tungsten filament while strikes to the mounted sample, they result in production of secondary electrons, X-rays, back-scattered electrons, diffused electrons etc. The X-rays produced from sample gives the measure of EDS spectrum. SEM micrographs can be generated at or above unit nanometer. In present study, the SEM micrographs were taken at different magnification scales like 100x, 350x, 500x, 1000x and 2000x according to the requirement of representation.

Surface morphology of sand particles

Sand/silt samples were collected from the Nathpa Jhakri Dam, Kinnaur, Himachal Pradesh (India). The surface morphology of sand particles is shown in Figure 3.5. SEM micrographs were carried out at different magnifications like 350x, 500x, 1000x. From micrographs, the irregularities and sharp edges can be observed on the surface of sand particles. The shapes of sand particles seem to be random throughout the SEM micrographs. Similar observation was made by other researchers (Kishor et al. 2016a, 2016b; Kishor et al. 2018).

Surface morphology of fly ash particles

Figure 3.6 represents the morphological structure of fly ash particles at different magnifications. From Figure 3.6, it is visualized that the surface of fly ash particles was smooth and most of the particles have spherical shape. The smaller fly ash particles seem to be agglomerated. Many of the small particles were identical to cenospheres (hollowspheres).

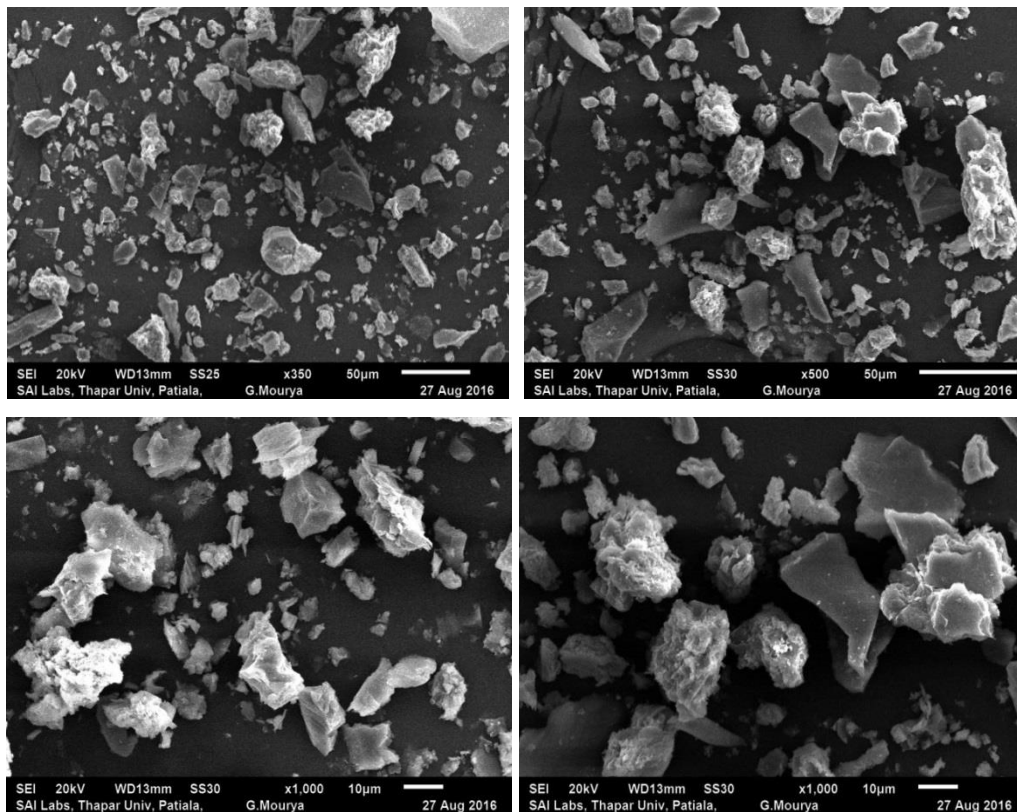


Figure 3.5. SEM micrographs of sand particles at different magnification.

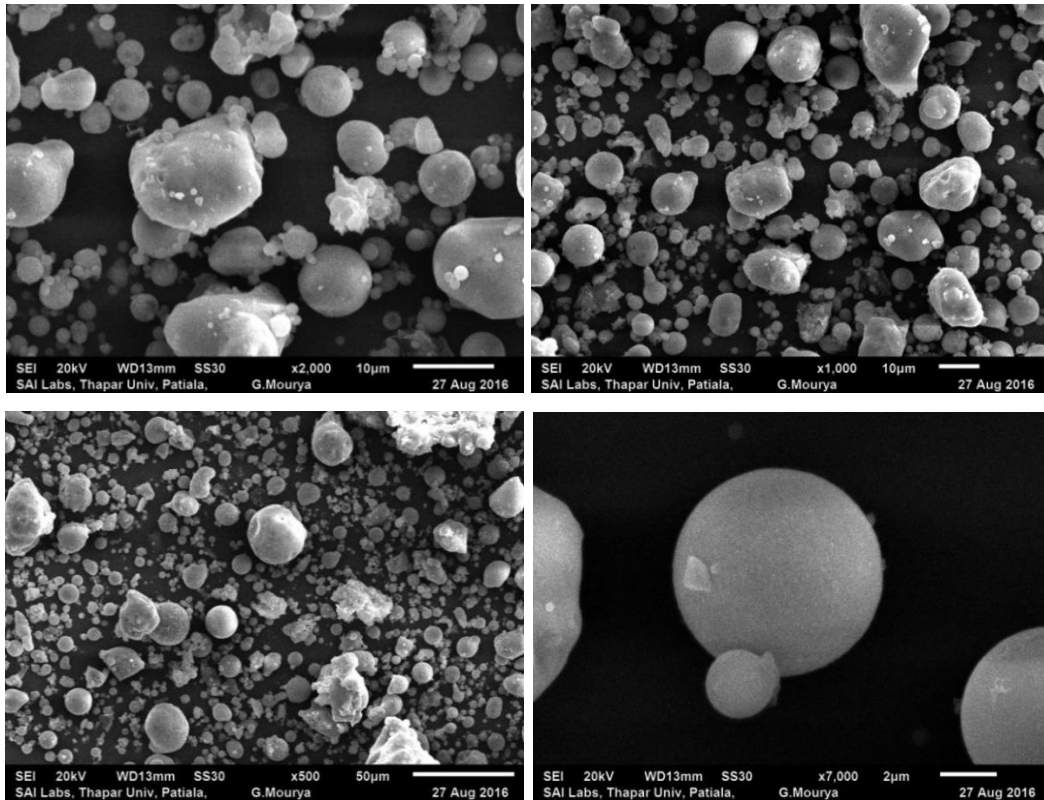


Figure 3.6. SEM micrographs of fly ash particles at different magnification.

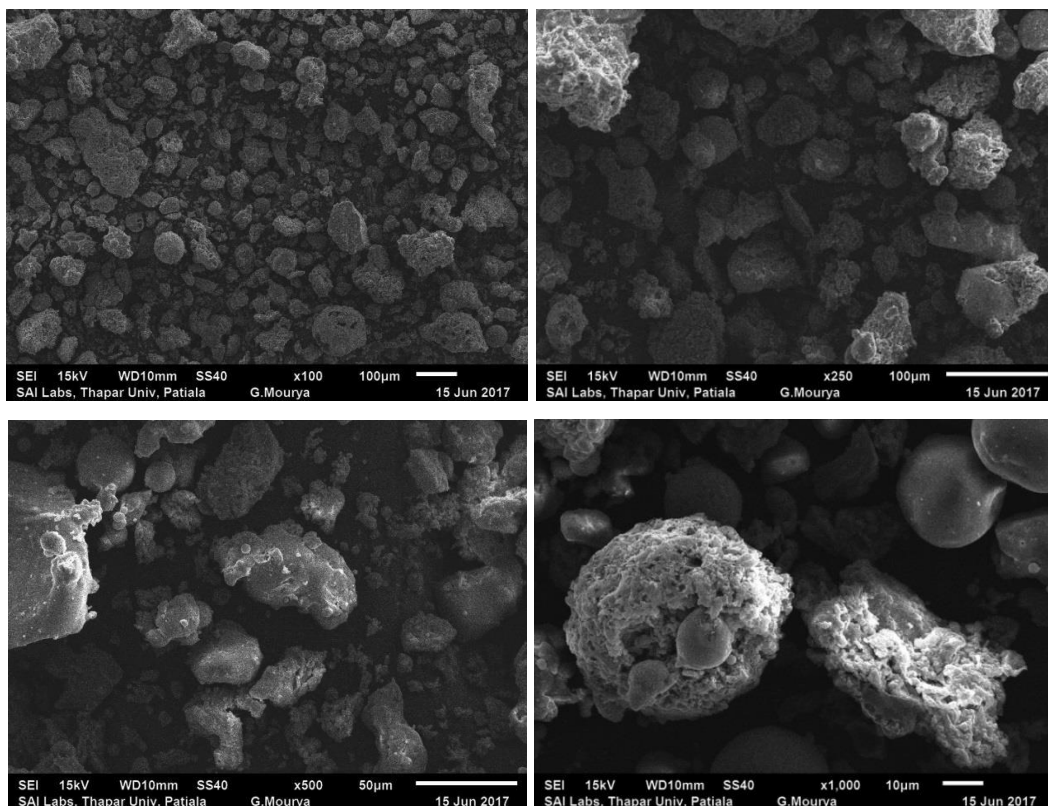


Figure 3.7. Surface micrographs of bottom ash particles at different magnification.

Surface morphology of bottom ash particles

The surface morphology of bottom ash particles is shown in Figure 3.7. From SEM micrographs, the bottom ash particles were found irregular and blocky in shape. These particles seem relatively coarser than fly ash particles. The surface appearance of these particles highlights the pores and clustering of different elements/compounds. The general observation of surface morphology of fly and bottom ash shows the close agreement with other researchers (Mishra and Das, 2010; Mishra and Das, 2010; Kumar et al. 2016; Kumar et al. 2017)

3.2.2 Compositional analysis

The chemical composition of erodent, coated and eroded samples was determined by using energy dispersive spectroscope (EDS) which was equipped with a scanning electron microscope (SEM). EDS is also known as the EDX i.e. Energy-dispersive X-ray spectroscopy (EDX). In present study, the EDS spectrums were also used to perform the mapping of different elements in coated samples. As mentioned in above section (3.2.1), The X-rays produced when the electron beams from filament strikes to sample. In EDS, an interaction occurs between X-rays excitation and sample specimen that allows a distinctive set of peaks on its electromagnetic (Em) emission spectrum. The mounted sample consists of different elements and each of elements has a unique atomic structure. The energies produced from the sample surface by X-rays interaction are measured by an energy-dispersive spectrometer. The variation in produced energies of X-rays gives the measure of elemental composition. The EDS spectrums comes with limitation also, the energy levels of many elements resemble to each other in that case the accuracy of EDS spectrum decreases.

Table 3.1: EDS data of sand sample

Spectrum	Element (wt. %)							
	Na ₂ O	Al ₂ O ₃	SiO ₂	K ₂ O	FeO	C	CaO	MgO
1	1.66	35.83	53.92	8.59	-	-	-	-
2	1.18	14.94	77.74	3.16	2.98	-	-	-
3	-	1.74	4.25	30.94	0.83	62.25	-	-
5	-	22.95	41.95	10.37	4.96	-	17.67	2.11

Chemical composition of sand

The EDS spectrums of sand particles are shown in Figure 3.8. From EDS spectrums, the average chemical composition of different elements in sand particles was evaluated. It was found that alumina (Al_2O_3) and silica (SiO_2) was the major content in sand particles. The data obtained from EDS spectrums is listed in Table 3.1.

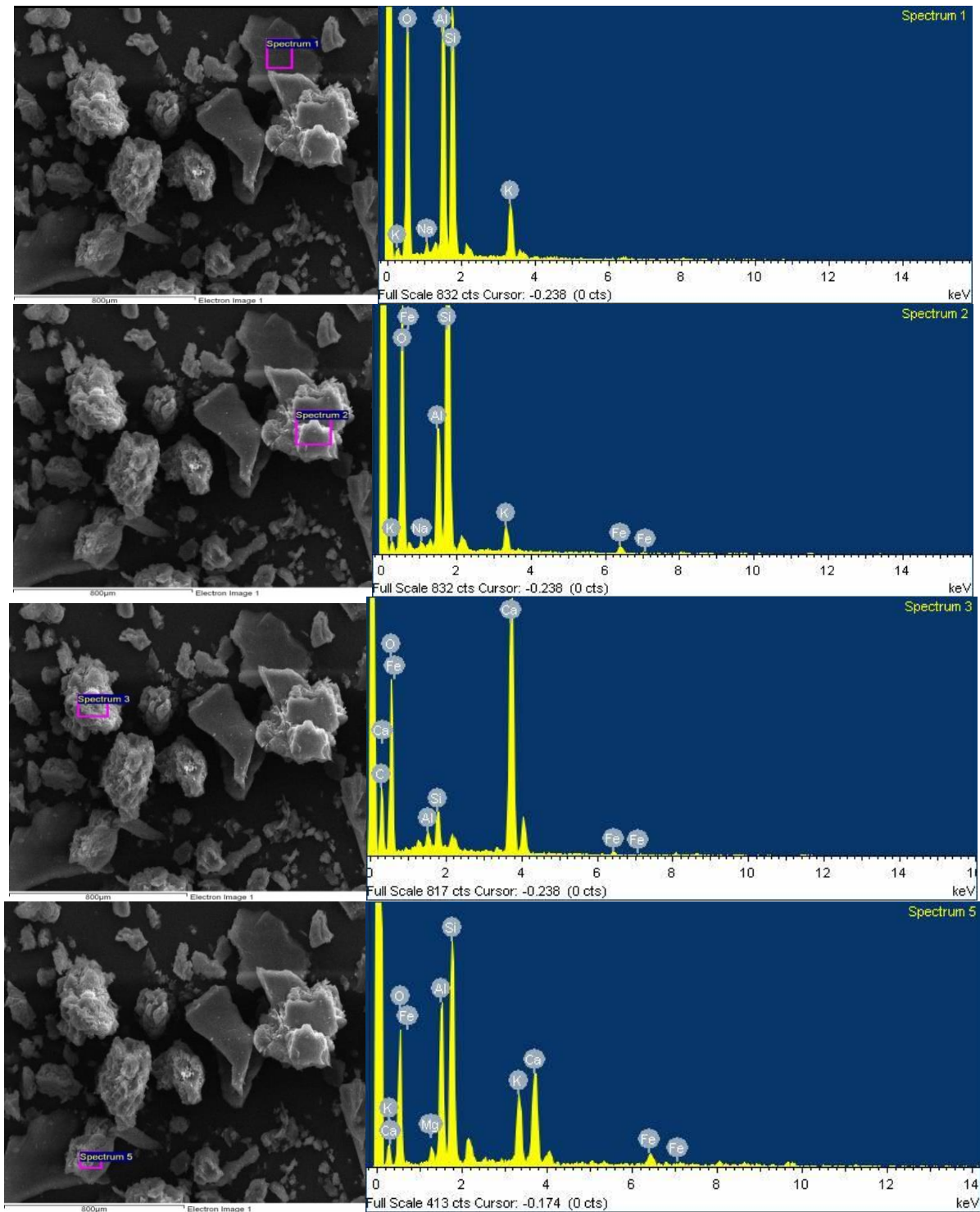


Figure 3.8. Electron dispersive spectroscopy (EDS) of sand.

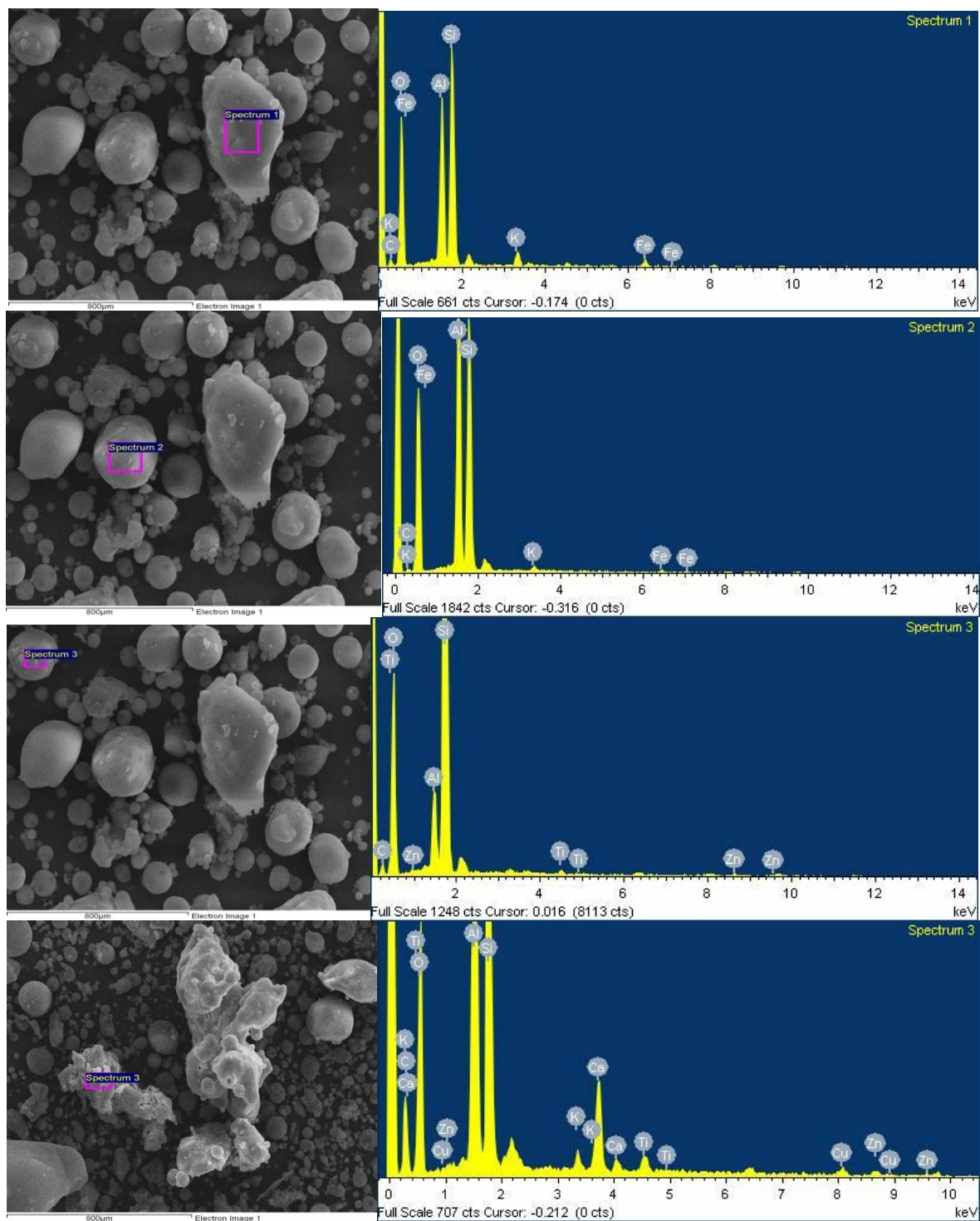


Figure 3.9. Electron dispersive spectroscopy (EDS) of fly ash.

Chemical composition of fly ash

The EDS spectrums of fly ash particles are shown in Figure 3.9. The chemical composition of fly ash samples show that alumina and silica were present in major proportion. In EDS spectrums of fly ash few of the heavy metals like titanium, potassium, magnesium, zinc, iron and calcium, as listed in Table 3.2. The compositional data of fly ash shows the close agreement with the previous studies (Kumar et al. 2014 and 2016).

Table 3.2: EDS data of fly ash sample

Spectrum	Element (wt. %)								
	TiO ₂	Al ₂ O ₃	SiO ₂	K ₂ O	FeO	C	CaO	MgO	ZnO
1	1.53	26.17	54.63	0.61	6.34	-	1.41	9.31	-
2	-	36.58	46.54	0.56	0.84	15.48	-	-	-
3	0.73	5.46	64.80	-	-	27.97	-	-	1.03
3	1.43	24.60	50.76	0.57	5.94	6.56	1.31	8.82	-

Table 3.3: EDS data of bottom ash sample

Spectrum	Element (wt. %)										
	CuO	Al ₂ O ₃	SiO ₂	K ₂ O	FeO	C	CaO	MgO	CdO	PbO	Co ₂ O ₃
1	5.95	23.66	23.73	7.26	19.06	1.3	6.81	-	6.19	6.03	-
2	-	23.16	35.96	8.27	8.62	1.1	-	7.26	-	7.8	-
3	-	21.83	26.68	6.06	9.18	0.6	5.64	4.06	-	6.67	6.63
4	-	22.31	26.37	0.42	2.18	-	0.96	-	0.87	1.46	2.94

Chemical composition of bottom ash

The EDS spectrums of bottom ash particles are shown in Figure 3.10. It was found that the percentages of silica, alumina and lead were the major contents bottom ash samples. The compound compositions of bottom ash samples are tabulated in Table 3.3. The microhardness of alumina and silica is usually high which contributes in erosion wear of different materials (Desale et al. 2009; Walker and Humbe, 2015). Also, the presence of these particles contributes in drag affect during the flow (Mosa et al. 2008).

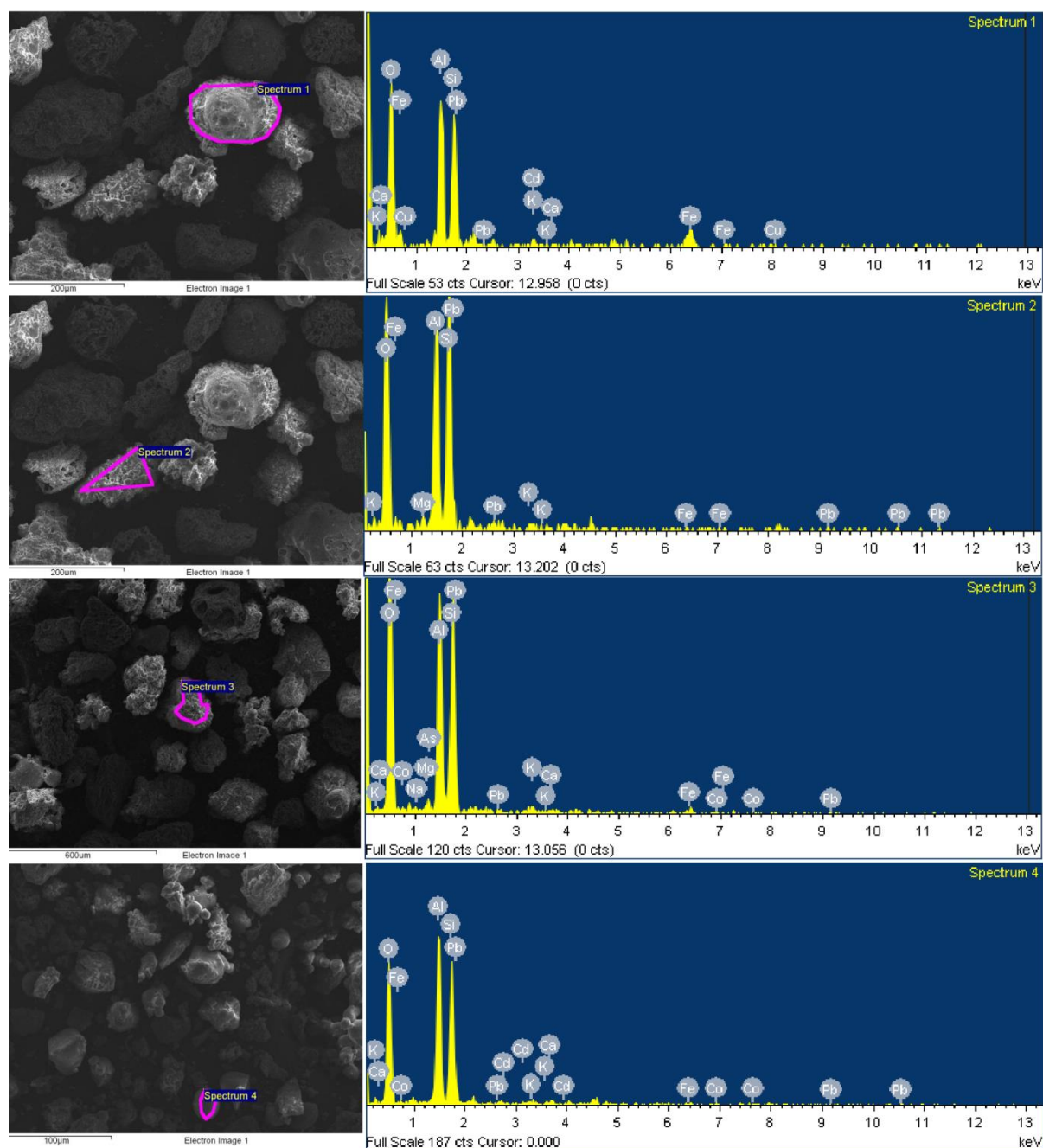


Figure 3.10. Electron dispersive spectroscopy (EDS) of bottom ash.

3.2.3 Crystallographic analysis

Crystallographic analysis was done by performing the X-ray diffractometry (XRD) of sand, bottom ash and fly ash samples. X-ray diffraction is well-known technique to identify of unknown crystalline materials and phases present in different solid materials. In present investigation, X-ray Diffractometry was used to identify the various crystalline phases of different compounds present in erodent materials and coated surfaces.



Figure 3.11. Sample holder for XRD.

Preparation of samples for XRD

The sample preparation is done in sample holder, illustrated in Figure 3.11. Prior to sample preparation the, sample holder was cleaned with acetone to remove impurities from it. Afterward, a powdered sample of few grams quantity was put in cavity of sample holder. Then, the filled cavity was made plane as the surface of sample holder by using a glass piece. For metallic or coated samples, a square shape sample of 2×2 cm having thickness of 5 mm was prepared. Then, it was put in cavity of sample holder for XRD analysis.

Working Principle

An X-ray Diffractometer consists of an X-ray tube, specimen holder, goniometer and detector. A high voltage electron beam is generated from the X-ray tube. The specimen fixed in sample holder rotates at an angle ' θ '. The rotation of X-ray detector is angle ' 2θ '. Goniometer is used to set the angle of rotation of sample. The working principle of XRD is Diffractometry which follows the Bragg's equation. According to this principle, while the electron beams strike to the different materials they gets diffracted or back-scattered or diffused. The position and intensity of diffracted X-rays is measured on detector which records the signal in terms of count rate. The count rate is further used to identify the presence of different phases. The wavelength of X-rays is represented by the spacing between crystals used to produce the diffraction pattern ($1-100 \text{ \AA}$). In present study, A Philips X'Pert diffractometer (Model: PW 1710) was used to obtain the X-ray diffraction patterns of erodent materials and coated surfaces. It was operated at 40 kV and 30 mA utilizing a reference Cu K α radiation ($\lambda=1.542 \text{ \AA}$). The value of theta was varied from 10° to 100° in present work.

XRD of sand particles

An XRD spectrum of sand particles is shown in Figure 3.12. It can be seen that the quartz (SiO_2) was seen in maximum number of counts. Other crystalline phases such as periclase (MgO), quick lime (CaO) and aloxite or alumina (Al_2O_3). Highest intensive peak in XRD spectrum was formed by quartz $2\theta=26.72^\circ$ which represents the presence of large quantity existence of quartz. XRD data shows close agreement with other researchers (Grewal et al. 2013a, 2013b).

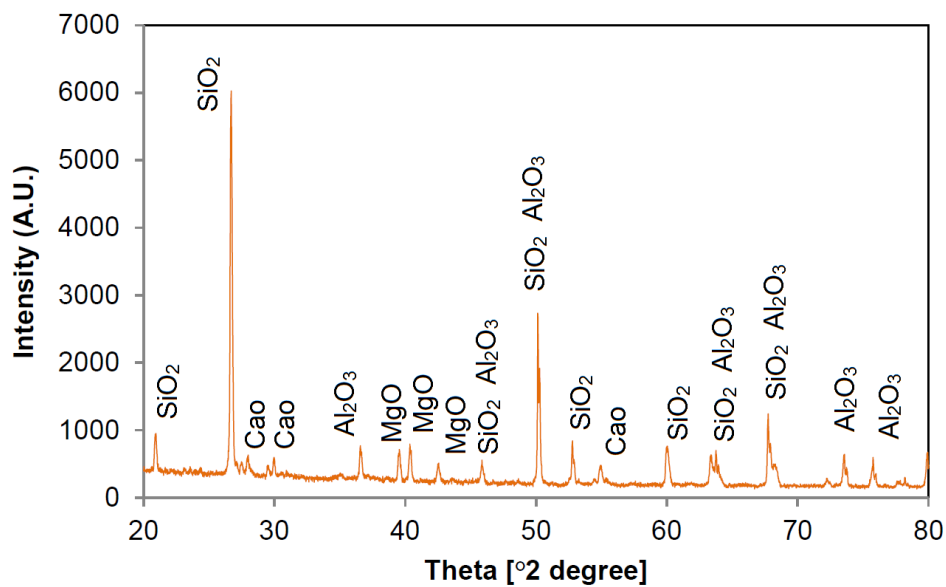


Figure 3.12. XRD spectrum of sand particles.

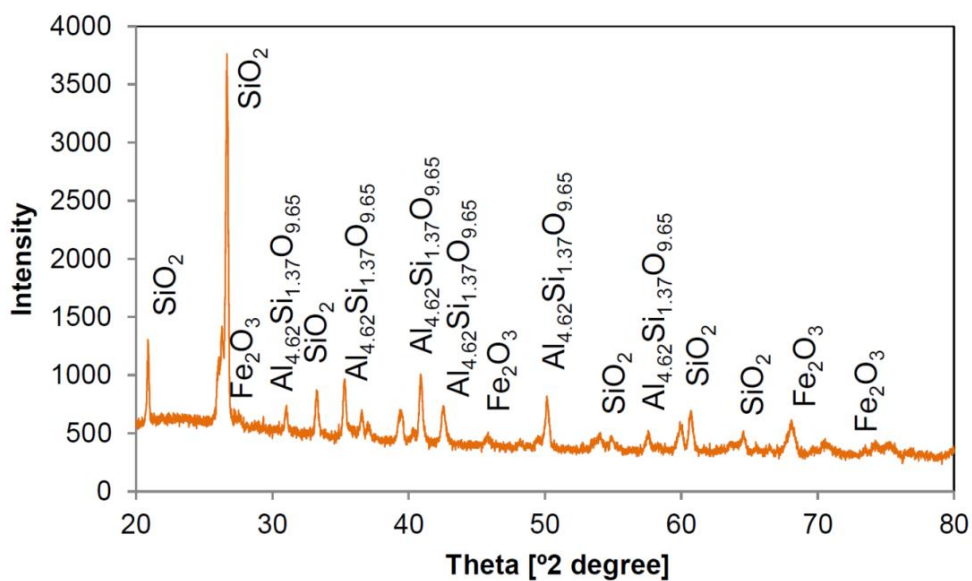


Figure 3.13. XRD spectrum of fly ash particles.

XRD of fly ash particles

The XRD spectrum of fly ash particles is shown in Figure 3.13. The crystalline phases found in fly ash particles were quartz (SiO_2), mullite ($\text{Al}_{4.62}\text{Si}_{1.37}\text{O}_{9.65}$), hematite (Fe_2O_3) and kyanite (Al_2SiO_5). Quartz form the highest intensive peak in XRD spectrum of fly ash also and its intensity was measured as $2\theta=26.68^\circ$. The XRD spectrum reports the crystalline nature of quartz phase amorphous nature. The small peaks were formed by the hematite crystalline phase (Fe_2O_3) that represents its existence in minor proportion. Similar observation was made by researchers (Kumar et al. 2013; Kumar et al. 2014; Kumar et al. 2016)

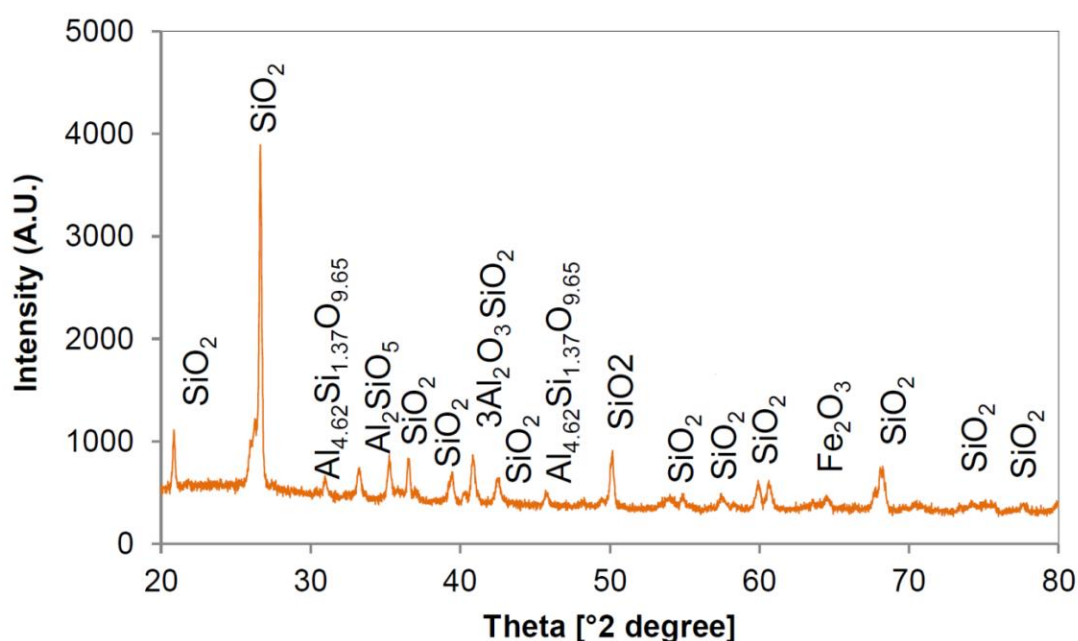


Figure 3.14. XRD spectrum of bottom ash particles.

XRD of bottom ash particles

The XRD spectrum of bottom ash particles revealed the presence of crystalline phases namely quartz (SiO_2), mullite ($\text{Al}_{4.62}\text{Si}_{1.37}\text{O}_{9.65}$), hematite (Fe_2O_3) and kyanite (Al_2SiO_5), as shown in Figure 3.14. Quartz has found the maximum peak in XRD spectrum of bottom ash particles. Also, the presence of mullite was higher as compared to the hematite. The strongest peak (2θ) of quartz in bottom ash sample was found as found as 26.624° . Smallest peak was formed by of hematite at an angle of 75.97° .

3.3 BENCH-SCALE ANALYSES

Various bench scale tests were performed to analyze the pH value, specific gravity, static settled concentration and rheological characteristics of slurry prepared from sand, fly ash and bottom ash.

3.3.1 Particle size distribution

Sieve analysis was carried out to obtain the particle size distribution of fly ash, bottom ash and sand particles. A sieve shaker (manufactured by Mody Testing Instruments Co. Vadodara, Gujarat, India) with British standard sieves was used in present work to carry out the particle size distribution.

Procedure adopted for sieving

Prior to sieve test, the powdered samples namely sand, fly ash and bottom ash were dried in an oven. The temperature of sample was uniformly maintained during this process. Afterward, the adjustments of sieves were done to obtain the different particle size ranges of powdered samples. The sieves are adjusted in a column. The arrangement of sieves was done in ascending order of BSS (British standard size) no. i.e. mesh of lowest BSS no. was kept on top and highest BSS no. mesh size placed at bottom. The bottom of these sieves is called as receiver or round pan. A 1000 gm of powdered samples was poured into the top sieve. Then, the sieve shaker was switched ON and kept for 15-20 minutes. Afterwards, the weight retained in different sieves was measured by using a CAY-220 electron weighing machine (manufactured by CAS Corporation, India) of 0.0001 g least count.

Particle size distribution results

The repeatability was taken into account by carrying out for the each test four times to ensure the accuracy in result data. The sieve analysis was carried out to obtain the different particles size ranges <53, 53-75, 75-106, 106-150, 150-250, 250-355 and 355-425. After performing the sieving of samples, the data of weights retained in each sieve was plotted between particle size range and percentages finer. The percentage finer was calculated by using the following equation:

$$\% \text{ finer} = \frac{R_w}{T_w} \times 100 \quad (3.1)$$

Where, R_w and T_w represent the weight of solid retained in sieve and total weight of solid in all sieves (grams). The particle size distribution of sand, fly ash and bottom ash is represented by Figure 3.15. From Figure 3.15, it is observed that only 7.23% particles of fly ash are finer than 150 μm , 5.2 particles are coarser than 250 μm , and 72.8% particles are finer than 75 μm . The PSD data of fly ash particles represents their finer nature. From results data of sand particles, it was observed that about 16.8% particles are coarser than 250 μm , 71.5% particles are in the range of 75 to 250 μm and only 5% particles are below 75 μm . It can be concluded that sand particles were coarser in nature. From PSD results, the 7.23% bottom ash particles are found finer than 75 μm , 8.7% particles lies in range 75-150 μm , 81.5% particles were coarser than 150 μm .

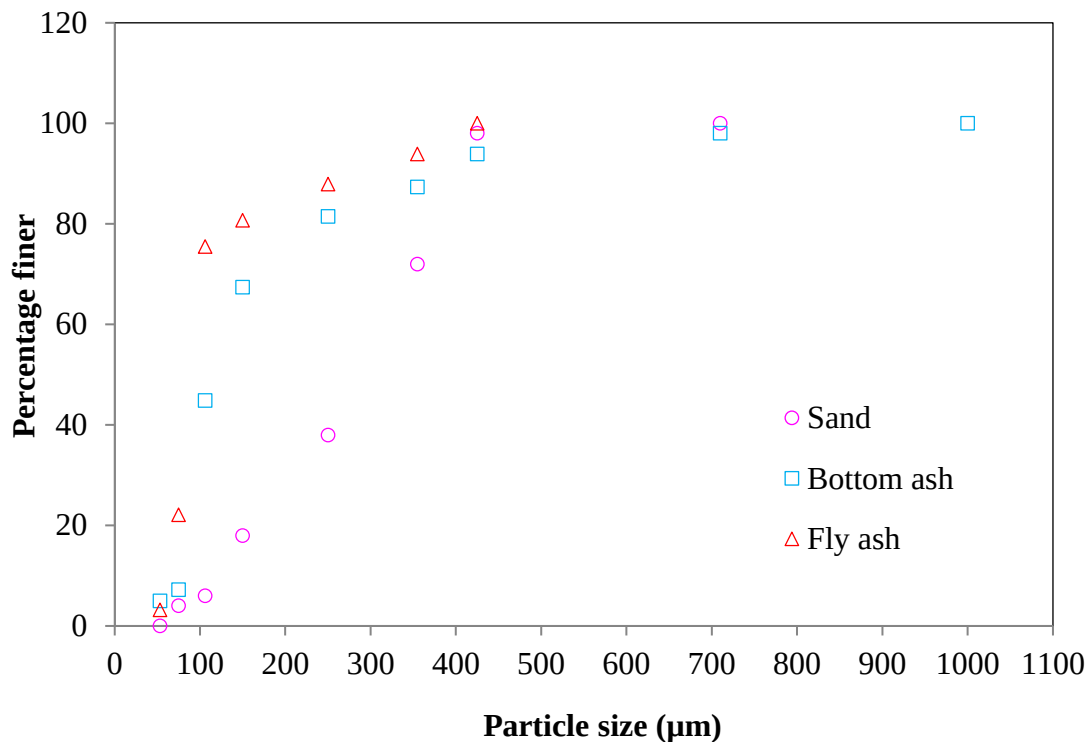


Figure 3.15. Particle size distribution of sand, fly ash and bottom ash.

Average fineness number

The differential analysis of the size distribution was carried out to calculate the average fineness number (AFN) of sand, fly ash and bottom ash particles. Following expression was used to determine the average fineness number (AFN) of sand sample:

$$AFN = \frac{\sum(M_i \times (m_i \times g))}{\sum(m_i \times g)} \quad (3.2)$$

In above equation, ‘ g ’ is the gravitational constant, ‘ $\sum(m_i)$ ’ represents the sum of mass retained in each sieve, and ‘ M_i ’ represents the British sieve standard (BSS) multiplier. Average fineness number (AFN) of sand sample with particle size distribution is summarized in Table 3.4. From Table 3.4, the BSS (British standard sieve) number of sand particles was found as 78.6 in range (82-72). The average fineness number (AFN) of sand particles was found as 195 μm in standardized range 180-210 μm .

Table 3.4: Particle size distribution of sand sample

S. No.	PSD range (μm)	BSS No.	W_i	M_i
1	< 53	300	2	600
2	53-75	200	2	400
3	75-106	150	4	600
4	106-150	100	12	1200
5	150-180	85	20	1700
6	180-255	60	32	1920
7	255-300	52	26	1352
8	>300	44	2	88
			$\sum W_i = 100 \text{ g}$	$\sum M_i = 7860$

Average fineness number (AFN) of fly ash sample with particle size distribution is illustrated in Table 3.5. The BSS number of fly ash particles lies in range 170-200 (~ 189) and the average fineness number (AFN) of lies in range 75-90 μm ($\sim 82.5 \mu\text{m}$). The BSS number of bottom ash particles was found as 120.22 (~ 120) and the average fineness number (AFN) of lies in range $\sim 125 \mu\text{m}$, as illustrated in Table 3.6.

Table 3.5: Particle size distribution of fly ash sample

S. No.	PSD range (μm)	BSS No.	W_i	M_i
1	< 53	300	18.89	5667
2	53-75	200	53.41	10682
3	75-106	150	5.20	780
4	106-150	100	7.23	723
5	150-180	85	5.97	507.45
6	180-255	60	4.10	246
7	255-300	52	3.20	166.4
8	>300	44	2.00	88
			$\sum W_i=100 \text{ g}$	$\sum M_i= 18859.85$

Table 3.6: Particle size distribution of bottom ash sample

S. No.	PSD range (μm)	BSS No.	W_i	M_i
1	< 53	300	5.00	1500
2	53-75	200	2.23	446
3	75-106	150	37.65	5647.5
4	106-150	100	22.52	2252
5	150-180	85	14.10	1198.5
6	180-255	60	5.80	348
7	255-300	52	8.95	465.4
8	>300	44	3.75	165
			$\sum W_i=100 \text{ g}$	$\sum M_i=12022.4$

3.3.2 Potential of hydrogen (pH value)

The potential of hydrogen (pH value) is the terms which is used to define the chemical nature of a particular liquid or solution. The pH value of an aqueous solution is the negative log of its hydrogen ions. Basically, the pH value of acids is below 7 whereas greater than 7 for alkaline (basic). The pH value of a neutral solution remains equals to zero for example water. It can be easily measured by using a digital pH meter. In the present investigation, a digital pH meter was used to determine pH value of the sand, fly ash and bottom ash slurry suspensions at different solid concentration. The pH meter (manufactured by: Orino 5 Star; pH ISE Cond DO BencTop) is associated with a glass electrode. Prior to analysis, electrode of

the meter was calibrated by using the aqueous solution i.e. distilled water. Afterwards, it was again washed by using the distilled water then immersed in the different slurries to examine their pH value. The pH value of sand slurry was found in range 7.71-7.16. The nature of sand slurry was found as alkaline. The pH value of fly ash slurry was found in range 6.32 to 6.09 while concentration was varied in range 30-60%. The pH value to fly ash seems to be weak acidic in nature. The pH value of bottom ash slurry lies in the range of 7.51 to 7.34 while the concentration was varied in range 30-60%. This also shows the alkaline nature of bottom slurry. Furthermore, the concentration of slurries has almost negligible effect on pH value which indicates non-reactive nature of slurries (Kumar, 2014).

3.3.3 Specific gravity

Specific gravity is the ratio of measured density of a substance to the density of a reference substance. The term ‘density’ represents the mass of a unit volume. Specific gravity is can be defined by the following equation:

$$\text{Specific gravity} = \frac{\text{Density of slurry}}{\text{Density of water}} \quad (3.3)$$

Specific gravity plays an important role in deciding the static settled concentration of the different slurries. In present study, the pycnometer method was used to determine the specific gravity of sand, fly ash and bottom ash slurry. Firstly, a 100 ml beaker was taken and washed with water tap water. Afterward, it was kept into a microwave oven for 1 hour. Then, the beaker was kept on electron weighing machine (least count: 0.0001 gm), and its reading was measured then set to zero. The oven dried sample (W_s) was poured into beaker to obtain a weight of 30 grams. After the weighing of sample, the slurry of sample was prepared by mixing it with distilled water and stirred from 5-10 minutes to ensure proper mixing. The level of slurry in beaker was marked for further measurement. Afterward, the weight of slurry sample (W_{sw}) was again measured after an hour and it was subtracted from the measured weight of beaker to obtain the exact weight of slurry sample (W_{sw}). After this process, the weighing of water (W_w) was done by filling the same beaker at the earlier marked level.

The measured values were noted down and put in following correlation to calculate the specific density of particular slurry.

$$\text{Specific gravity} = \frac{W_s}{(W_w - W_{sw}) + W_s} \quad (3.4)$$

The specific gravity of sand, fly ash and bottom ash particles was calculated as 2.667, 2.259 and 2.081 respectively.

3.3.4 Static settled concentration

The static settled concentration of slurry suspension was determined by gravitational settling method. The static settled concentration of sand slurry at different concentrations is shown in Figure 3.16. The solid concentration of slurries was varied in range 30-60 wt.%. It was found that the maximum settled concentration of sand slurry was 56.96, 59.4, 61.36 and 72.35% at 30, 40, 50 and 60% solid concentration (wt.%). Settling rate was almost negligible after 120 minutes.

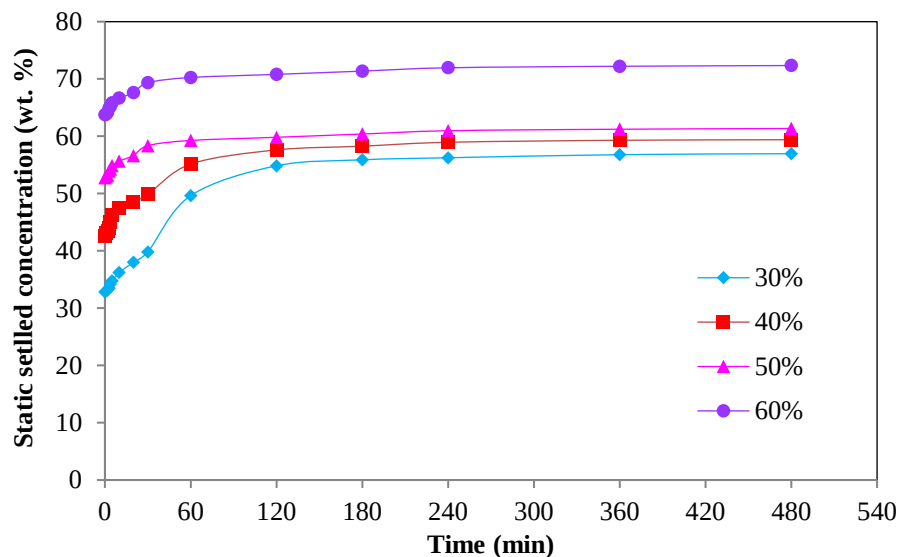


Figure 3.16. Static settled concentration of sand slurry different solid concentrations.

Similarly, the static settled concentration fly and bottom ash slurries was also measured. The static settled concentration (wt.%) of fly ash and bottom ash slurries is shown in Figures 3.17 and 3.18 respectively. The maximum settled concentration of fly ash slurry was found as 60.27, 63.06, 64.56 and 76.19% respectively at solid concentration of 30, 40, 50 and 60 wt.%. The maximum settled concentration of bottom ash slurry was found as 55.45, 57.89, 59.85 and 70.7% respectively at solid concentration of 30, 40, 50 and 60 wt.%. It was found that settling rate of fly ash slurry had become negligible after 180 minutes whereas for bottom ash slurry after 120 minutes (Kumar, 2014).

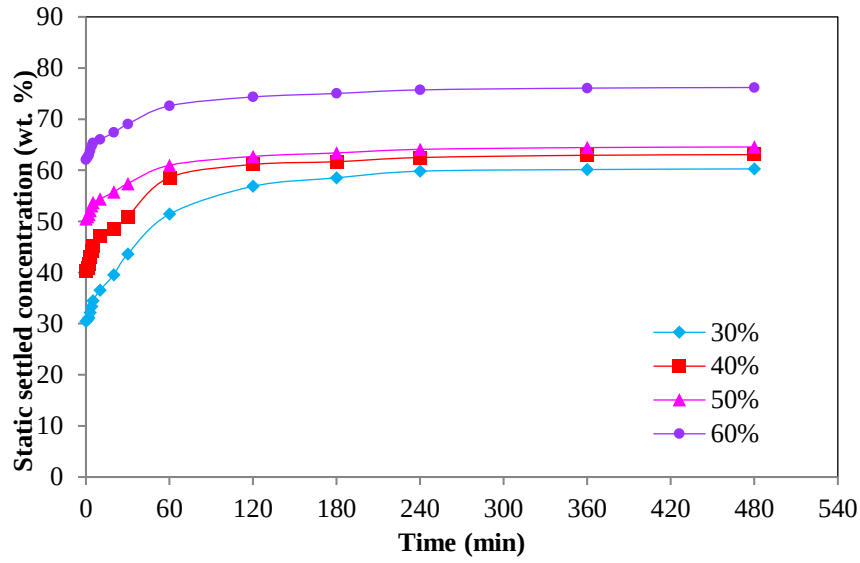


Figure 3.17. Static settled concentration of fly ash slurry different solid concentrations.

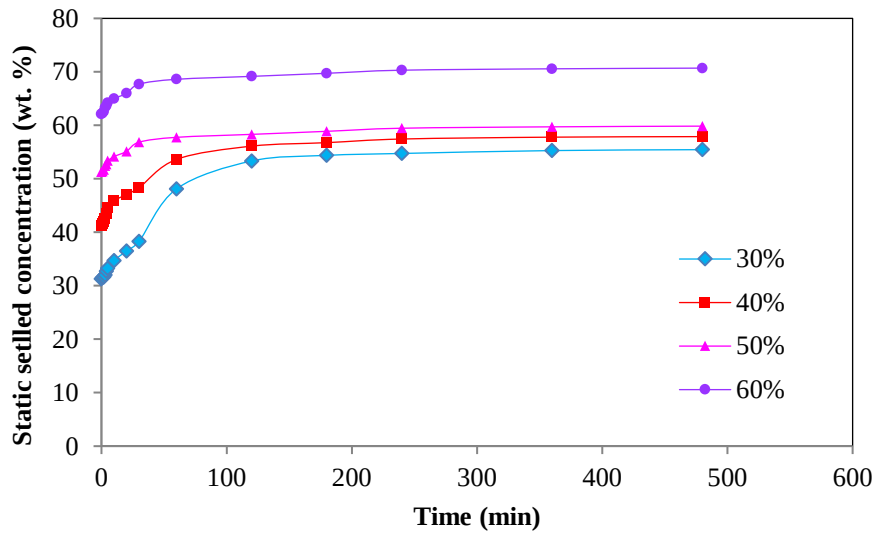


Figure 3.18. Static settled concentration of bottom ash slurry different solid concentrations.

3.4 IMAGE PROCESSING ANALYSIS

An image processing analysis (IPA) technique was used to measure the physical properties of the particles. In present work, image processing technique was used to measure the surface smoothness, circularity factor (CF), coefficient of variance (COV), sphericity (ψ) and solidity (κ) of particles. The magnification scale of SEM micrographs varied from $\times 500$ to $\times 2000$ during the scanning electron microscopy process, as recommended by researchers (Pichard, 1990; Walker and Humbe, 2015; Szala, 2016). Different tools were used to highlight the particles in the SEM image by using a threshold function. A Huang tool was used to adjust

the threshold of the SEM images. Figure 3.19 shows the methodology used for digital image processing. The particle measurements were carried out in ImageJ software package (Rasband, 1997).

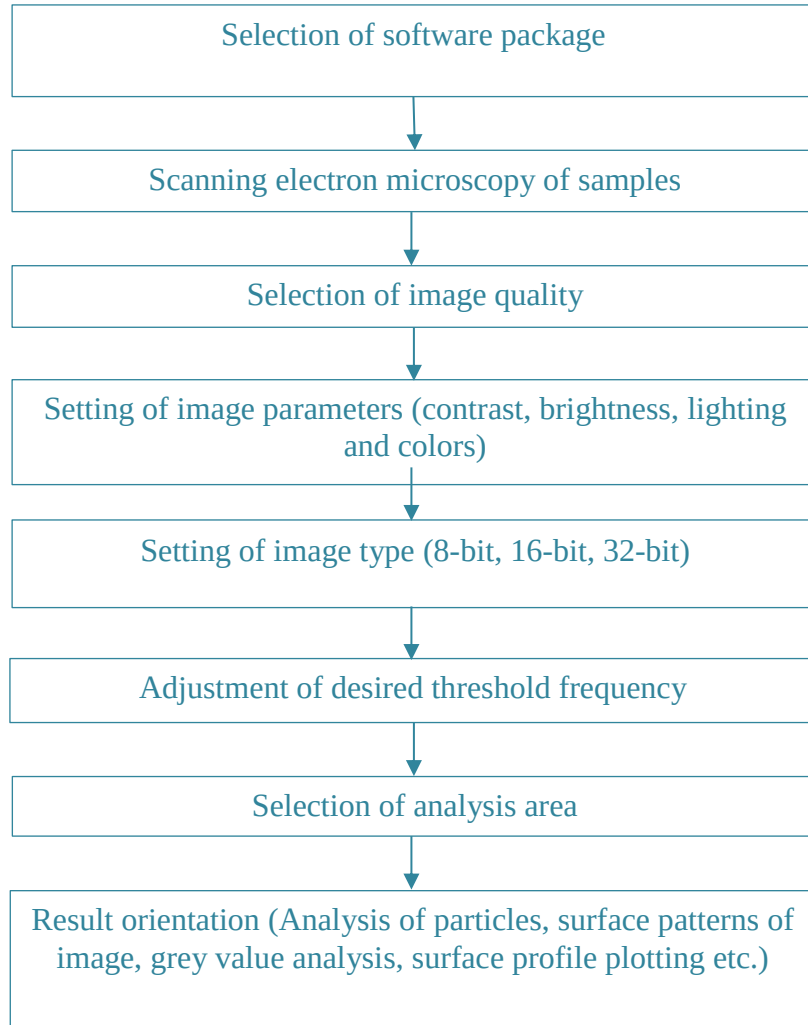


Figure 3.19. Flow chart of Digital image processing of SEM micrographs.

3.4.1 Surface smoothness analysis

The SEM images used for the shape analysis are represented in Figure 3.20. Based on the original SEM images, the surface profiles of fly ash, bottom ash, and sand have been generated. It can be seen that the grey pattern curve generated for fly ash particles has a low level of waviness, which represents the smooth surface of fly ash particles. The curve of bottom ash shows much waviness, which indicates the irregular surface of bottom ash. However, the curve generated for the surface of sand is comparatively smoother than bottom ash, which is also confirmed by the SEM images.

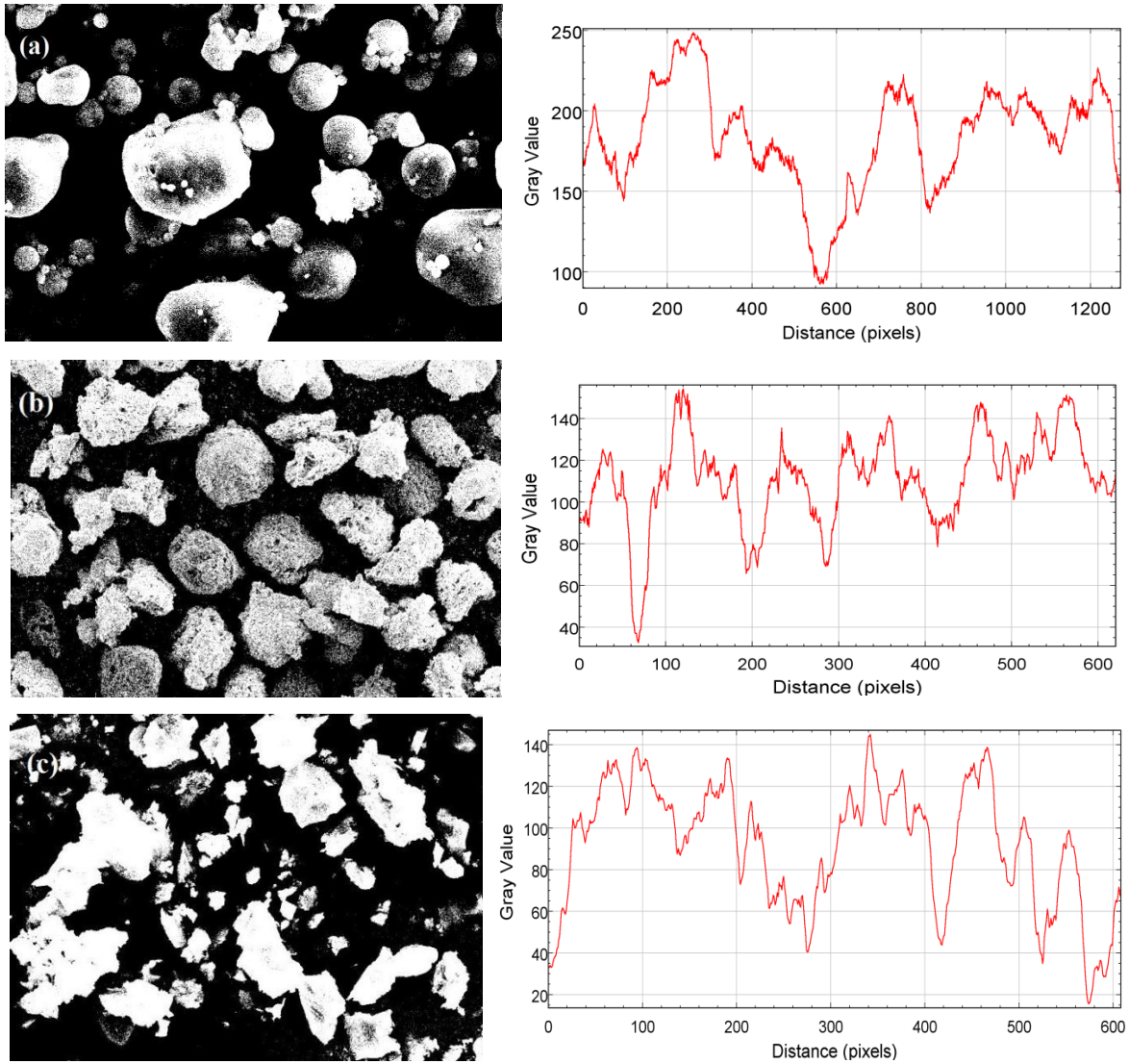


Figure 3.20. Threshold image analysis and surface profiles of (a) fly ash (b) bottom ash and (c) sand.

3.4.2 Circularity (*CF*) analysis

The particles' properties of multi-sized slurry obtained from the image processing procedure are summarized in Table 3.7. It was found that the *CF* of fly ash is 0.908, which is close to 1. According to Walker and Humbe (2015), spherical particles have higher shape factor than angular particles. The sand used in the present study is quite coarse, as it was collected from a dam. Due to this, the *CF* value of the sand in present experiments is very low (0.637), which indicates that the sand contains sharp edges and triangular-shaped particles. Generally, the value of *CF* for sand lies in the range 0.5 to 0.65 (Woldman et al. 2012). The bottom ash used in the present study was collected from an ash pond which contains a small quantity of

unburnt coal and fly ash. The average CF value of the bottom ash used in present experimentation was 0.712.

Table 3.7: CF values of multisized erodent particles

S. No.	Particles	Average value		
		CF	κ	COV
1	Fly ash	0.908	0.917	5.68%
2	Bottom ash	0.712	0.714	8.36%
3	Sand	0.637	0.952	10.1%

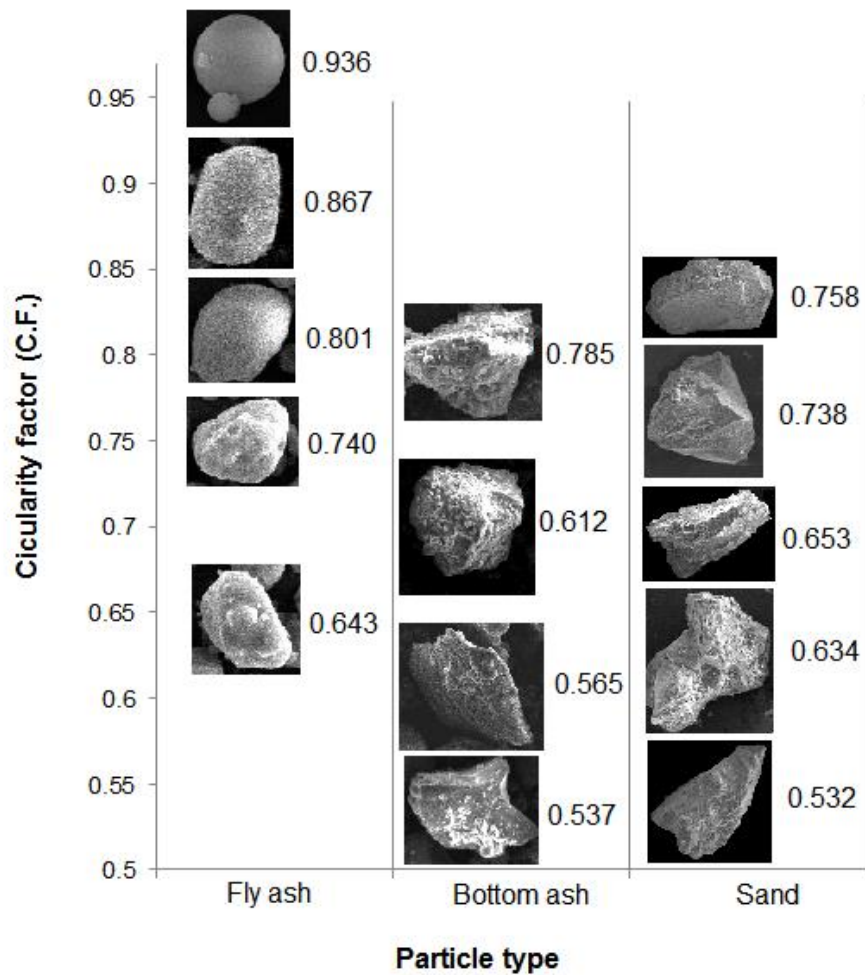


Figure 3.21. Various types of particle shapes with CF values.

Figure 3.21 represents the different types of shapes of solid particles with different CF values. Ranges of CF values were found as follows: for fly ash, $0.75 \leq CF \leq 0.95$; for bottom

ash, $0.55 \leq CF \leq 0.80$; and for sand, $0.5 \leq CF \leq 0.75$. In a few of the SEM micrographs, the fly ash particles had CF values of less than 0.75, which indicates the agglomeration of particles due to a charge or moisture; in the majority of the cases, fly ash had CF values equal to or greater than 0.75. Analysis of CF value was also carried out for equi-sized particle size distribution (PSD). Equi-sized PSD were prepared by separating the particle size ranges of fly ash, bottom ash and sand slurries. British standard sieves were used to carry out the particle size distribution (PSD) of erodents. Table 3.8 represents the CF value of equi-sized slurry obtained from the image processing.

Table 3.8: CF values of equi-sized erodent particles

S. No.	Particles	Particle size ranges				
		<53 μm	53-75 μm	75-106 μm	106-150 μm	>150 μm
1	Bottom ash	0.78	0.61	0.56	0.54	
2	Sand	0.76	0.65	0.63	0.53	
3	Fly ash	0.94	0.87	0.80	0.75	0.73

3.4.3 Sphericity (ψ) analysis

The sphericity of different types of particles was also measured during image analysis of the particles. The image processing tool used measured the perimeter of random particles and defined them by a ratio of sphere area to particle area (Trahan et al. 2014). The sphericity of particles was predicted by using following correlation (Zou and Yu, 1996):

$$\psi = \frac{A_s}{A_p} \quad (3.5)$$

In the above equation, A_s represents the area of the sphere, and A_p represents the area of the particles. The sphericity of randomly-distributed fly ash, bottom ash, and sand was measured as $0.90 \leq \psi \leq 0.98$, $0.78 \leq \psi \leq 0.89$, and $0.64 \leq \psi \leq 0.76$, respectively.

3.4.4 Solidity (κ) analysis

In the present study, the solidity of solid particles was also measured by using image processing. The image analysis tool measured the roughness and solidity of particles in terms of the grey values of the particles present in a particular SEM image. The solidity of particles was predicted by the correlation discussed by Liu et al. (2015). The average values of solidity

for fly ash, bottom ash, and sand are listed in Table 3.8. The solidity factors (κ) of randomly-distributed fly ash, bottom ash, and sand were measured in the ranges of 0.90-9.98, 0.78-0.89, and 0.64-0.76, respectively. The solidity factors of randomly-distributed fly ash, bottom ash, and sand were measured in the ranges of $0.89 \geq \kappa \leq 0.94$, $0.71 \geq \kappa \leq 0.93$ and $0.94 \geq \kappa \leq 0.96$ respectively. It seems that the value of κ for sand lies in a small range, whereas a large range exists for bottom ash particles. The value of κ remains close to 0.9 for fly ash. Solidity could not be completely considered in erosion wear experiments due to fact that the physically solid-surface material could be hollow inside, could contain soft elements, ductile, etc.

3.4.5 Effect of image parameters of response variable

The value of CF and solidity is also affected by the image quality. In the present study, SEM micrograph of fly ash was taken at four different qualities. Image 1, 2, 3 and 4 represents the normal image, high brightness, high brightness and contrast, and high brightness, contrast and saturation. From Figure 3.22, it can be observed that as the image lightening and contrast value increases the CF value and solidity also increases. These results follow the statement given by Pirard (1990).

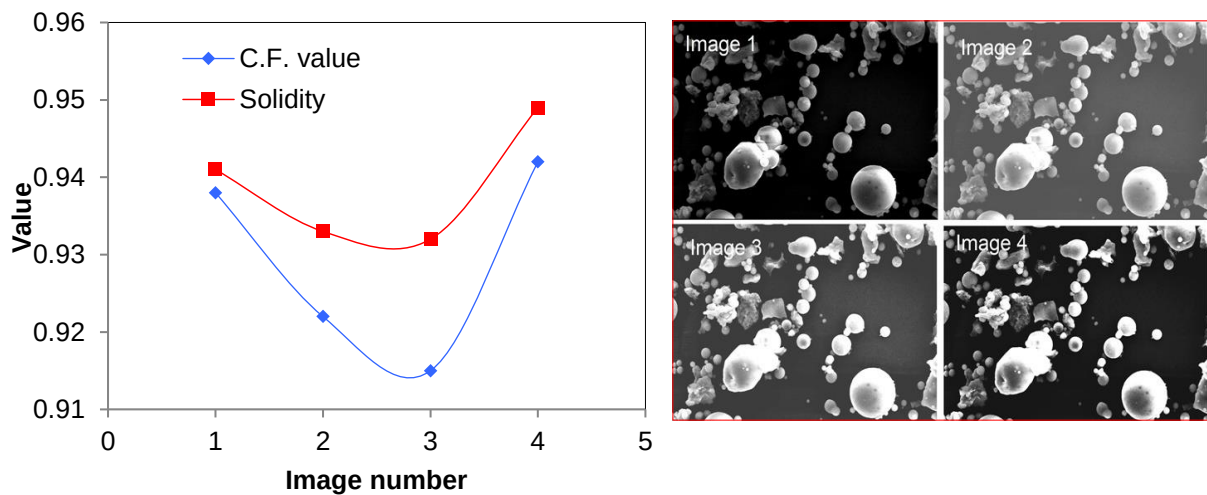


Figure 3.22. Effect of image lightening on CF value and solidity.

3.5 REMARKS

- The irregularities and sharp edges appear on the surface of sand particles. The surface of fly ash particles is smooth and has spherical shape. The smaller fly ash particles are

identical to cenospheres (hollowspheres). The bottom ash particles are found irregular and blocky in shape.

- Sand particles contain high percentage of alumina which has high microhardness (275-375 μm) so they can contribute in erosion wear of different materials.
- The particles of fly ash are finer in nature whereas the particles of bottom ash and sand are coarser in nature. The sand particles are coarser as compared to bottom ash particles.
- The specific gravity of for sand, fly ash and bottom ash particles is 2.667, 2.259 and 2.081 respectively.
- The bottom ash and sand slurry is alkaline in nature and fly ash shows weak acidic nature.
- CF values of different erodent materials are as follows: for fly ash, $0.75 \leq CF \leq 0.95$; for bottom ash, $0.55 \leq CF \leq 0.80$; and for sand, $0.5 \leq CF \leq 0.75$.
- The sphericity of randomly-distributed fly ash, bottom ash, and sand is lies in range: $0.90 \leq \psi \leq 0.98$, $0.78 \leq \psi \leq 0.89$, and $0.64 \leq \psi \leq 0.76$, respectively.

CHAPTER 4

EROSION WEAR OF PUMP MATERIALS: PART I

EROSION WEAR OF PUMP MATERIALS: PART I

4.1 SELECTION OF MATERIALS

Selection of materials is an essential part of controlling the erosion wear. In present investigation, four different pumping materials are selected on the basis of literature survey. These materials are universally used to fabricate the different components of slurry pump. The main reason of selecting these materials was their versatility in many applications excepting slurry pumps such as turbine blades, slurry pipelines, elbows etc. Moreover, the present investigation was aimed to study the erosion wear of pump materials used in slurry transportation systems of mining industry as well as thermal power plants. The solids processed through slurry pumps in these industries are entirely different in nature from each other. The pumping materials used in present investigation with application are listed in Table 4.1.

Table 4.1: List of pump materials used in present investigation

S. No.	Materials	Components	Application
1	Grey cast iron	Pump casings	Domestic and industrial centrifugal pumps
2	Stainless steel SS304	Pump impeller, casings, seals, valve seats	Centrifugal slurry pumps
3	Stainless steel SS316L	Pump impeller, casings, seals	Centrifugal slurry pumps
4	Super duplex stainless steel (SDSS2507)	Heavy duty pump impellers	Centrifugal slurry pumps mining and marine pumps

The grey cast iron is widely used to fabricate the pump casings. The cast iron is known for its high hardness. Cast iron is cheap and commercially available in market. Two other stainless steels are widely used as pump materials namely SS304 and SS316L. These are used to fabricate the pump impeller, casings and seals. In heavy duty erosion and corrosion conditions, super duplex stainless steels are widely used. In present study, super duplex

stainless steel (SDSS2507) was used which has application in fabrication of heavy duty pump impellers. SS316L was purchased from Pearl Overseas, Mumbai (Maharashtra, India). SDSS2507 was purchased from Jayant Ferromet LLP, Mumbai (Maharashtra, India). In this chapter, different metallographic analyses are also discussed which are performed before erosion wear experiments.

4.2 SAMPLE SPECIMEN

The fabrication of sample is also an important part of erosion wear experiments. The size of specimen was also optimized to perform the obstacle-free erosion wear experiments. At initial phase of experiments which were performed on SS304, the dimensions of specimen were kept as 76.2×25.4×6.35 mm. Erosion wear experiments were successfully performed but few drawbacks were observed during the experiments such as:

- Need extra time to load/unload specimen in pot tester.
- Required high level of control on jack during fixing the pot.
- Uncertainty of collision-free motion of specimen with buffers.
- Fully tight pot to avoid leakage of slurry.
- Constrained slurry flow.
- Desired level of temperature maintaining.

To overcome such problems, the sample specimens were redesigned in rectangular shape having dimension 67.5×25.4×6.35 mm with a central hole of 8.5 mm diameter for holding purpose in rotating spindle of the tester. The schematic diagram of sample specimen is shown in Figure 4.1.

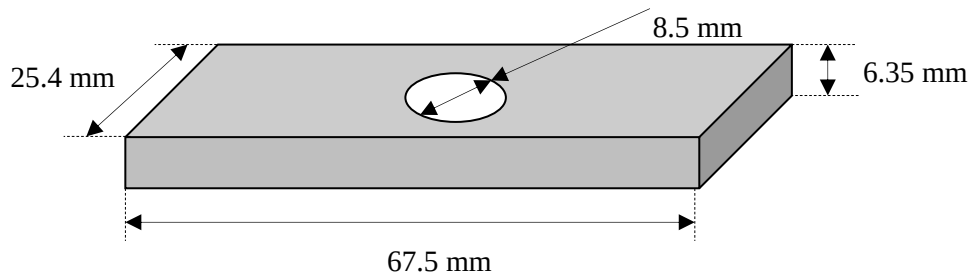


Figure 4.1. Geometry of sample specimen.

4.3 PRE-EXPERIMENTAL ANALYSIS

4.3.1 Sample preparation for metallographic analysis

The metallic samples were polished prior to metallographic investigation. The polishing of metallic samples (pump materials) was done in three stages. Initially, the metallic pieces were polished on sander machine. A belt type sander machine was used to provide the initial finishing of cast metallic pieces. This machining was done to provide as plan surface to the samples. Afterwards, the emery papers of grades 320, 600, 1000 and 2000 were used in ascending serial order to achieve the high surface finish. High level finish of metallic and coated samples was obtained by using a disc-type polishing machine. A disc-type polishing machine was used to polish the coated as well as metallic surface. At the end, the polished samples again processed to the cloth wheel for mirror finish.

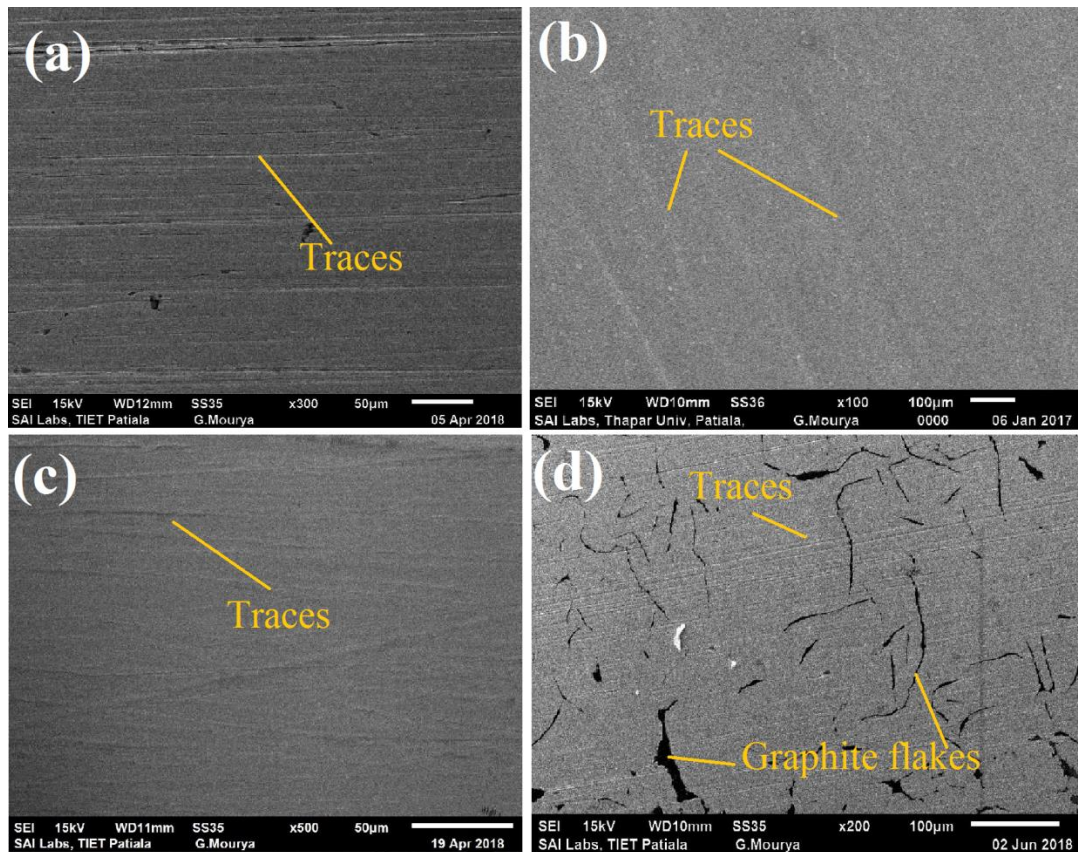


Figure 4.2. SEM micrographs of (a) SS316L, (b) SS304, (c) SDSS2507, and (d) Grey cast iron materials.

4.3.2 Surface morphology analysis

Surface morphology of different pump materials was analyzed by using the scanning electron microscopy (SEM). Samples were prepared by using the polishing procedure (discussed in

section 4.3.1). SEM was performed to make sure the low level of surface impurities to characterize the exact erosion wear mechanism after experiments. The SEM micrographs of different pump materials are shown in Figure 4.2. From Figure 4.2, very fine traces were visualized on the surface of SS316L, SS304 and SDSS2507 whereas the graphite flakes were appeared on the surface of grey cast iron. The grey cast iron seems to be pearlitic in nature.

4.3.3 Compositional Analysis

The chemical composition of pumping materials namely grey cast iron, stainless steel SS304, SS316L and super duplex stainless steel (SDSS2507) was measured. Chemical composition of ferrous materials can be precisely measured by using an optical emission spectrometer. The optical emission spectrometer manufactured by Foundry master, Oxford Instruments, Udem, Germany was used in present study. The chemical composition of materials was provided by the material supplier and measured from optical emission spectrometer is listed in Table 4.2 and 4.3 respectively. The measured compositional data shows close agreement with the data provided by supplier and available literature. Specimens used for optical emission spectroscopy are shown in Figure 4.3.

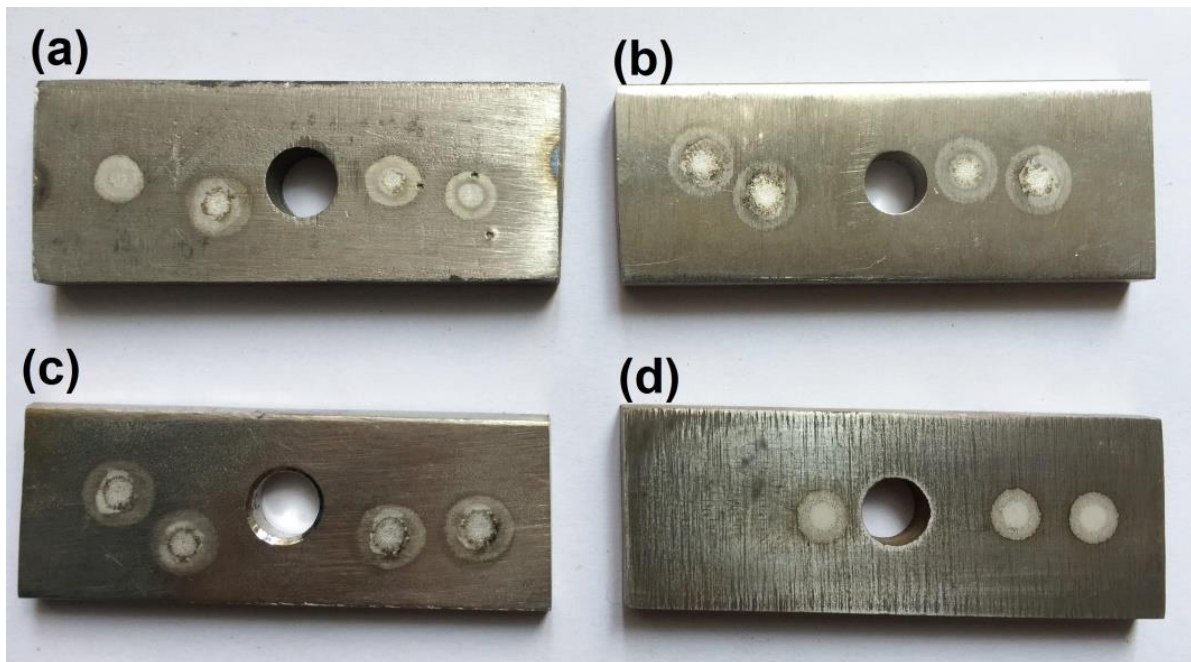


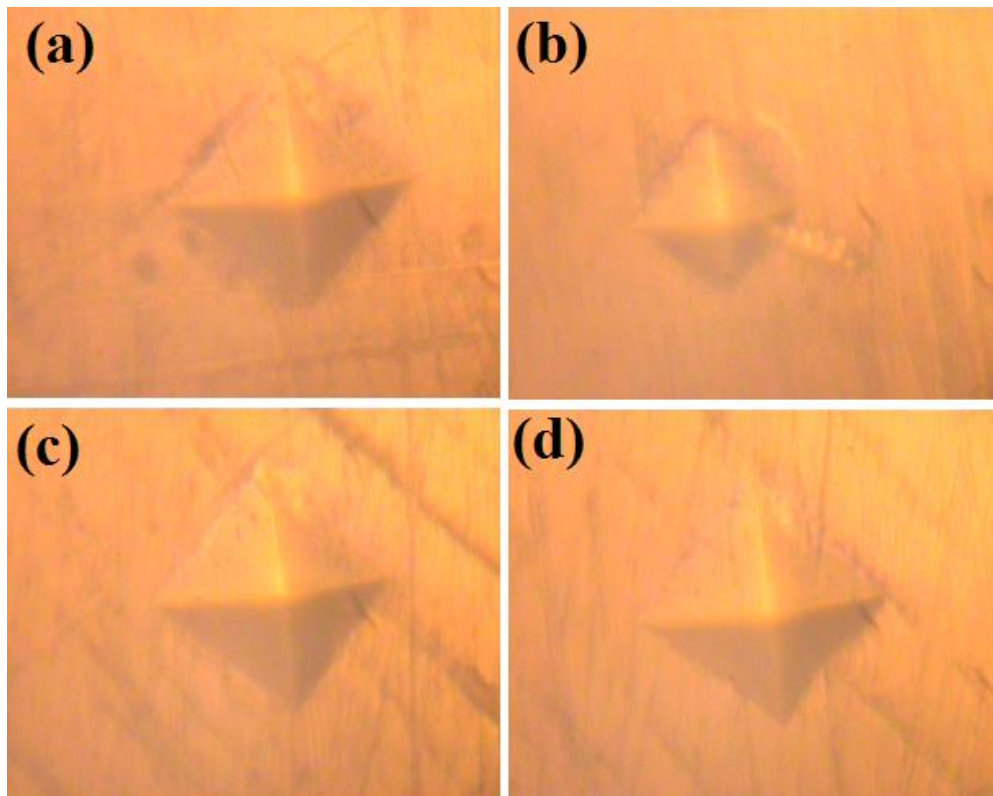
Figure 4.3. Optical emission spectroscopy of (a) SS316L, (b) SS304, (c) SDSS2507, and (d) Grey cast iron specimen.

Table 4.2: Compositional analysis of different pump materials by supplier

Material	Elements (%)										
	S	P	C	Mo	Mn	Si	Ni	Cr	Co	N	Fe
SS316L	0.0010	0.0130	0.016	3.010	1.130	0.470	10.230	16.320	0.89	---	Bal.
SDSS2507	0.001	---	0.02	4.00	---	---	7.00	25.00	---	0.27	Bal.

Table 4.3: Compositional analysis of different pump materials

Material	Elements (%)										
	S	P	C	Mo	Mn	Si	Ni	Cr	Co	N	Fe
SS316L	0.005	0.083	0.005	1.69	1.02	0.135	10.35	16.60	1.69	---	Bal.
SS304	0.025	0.015	0.08	---	3.64	0.31	7.96	18.04	---	---	Bal.
SDSS2507	0.011	---	0.035	3.96	---	---	5.99	23.98	---	0.21	Bal.
Grey C.I.	1.88	---	3.43	---	0.55	3.36	---	---	---	---	Bal.

**Figure 4.4. Typical indent observed on the surface of (a) SS304, (b) SS316L, (c) SDSS2507 and (d) Grey cast iron.**

4.3.4 Surface microhardness analysis

The microhardness of pumping materials was measured with digital micro hardness testing equipment (manufactured by Metatech MVH-1 Pune, India). During the testing, the indentation load varied from 500-1000 gm. The typical Vickers indentation marks on different coatings are shown in Figure 4.4. Experimental repeatability was accounted by testing the microhardness in 6 trails. Average microhardness of the SS304, SS316L, SDSS2507 and grey cast iron for 500 gm load was found as 237, 296, 212 and 207 H.V. respectively. The parallel and perpendicular Vickers diagonals were measured as 72.840 and 69.610 μm respectively for SS316L, 37.63 and 32.409 μm respectively for SS304, 45.962 and 46.718 μm respectively for SDSS2057 whereas 43.989 and 43.782 μm respectively for grey cast iron. To measure the accuracy of indentation marks, an indent on the surface of SS316L was measured by using Scanning electron microscopy. A SEM micrograph of indent made on the surface of SS316L is shown in Figure 4.5.

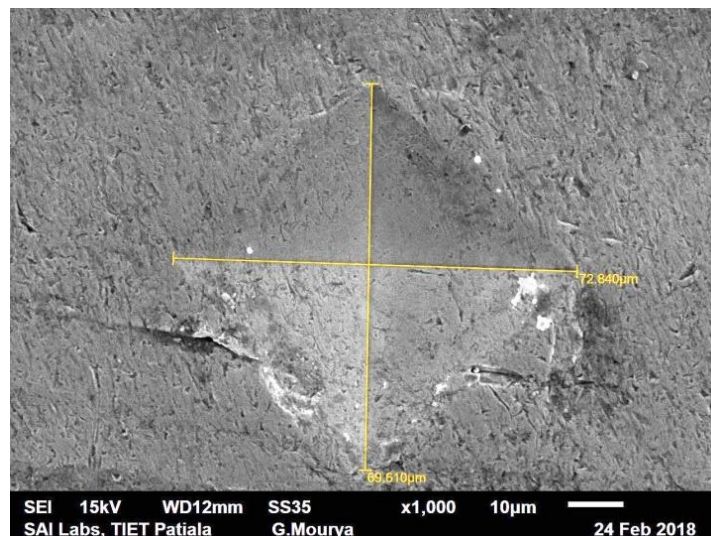


Figure 4.5. Typical indentation mark on the surface of SS316L.

4.4 DESIGN OF EXPERIMENTS

Design of experiment was implemented for optimization of erosion wear of pumping materials. Generally, the erosion wear parameters can't be optimized because erosion wear problem is directly associated with the increase or decrease of a particular parameter. Minimum the value of influencing parameters results in minimum value of erosion wear. According to objective of present study, it is important to identify the most influence

parameter among from different parameters. In this context, Taguchi's method was used to identify the most influencing parameter (Taguchi, 1990; Stojanovic et al. 2016; Veličković et al. 2016). Taguchi's Erosion wear was measured in the terms of weight loss (gm/m^2) with the help of electronic weighting machine of least count 1×10^{-4} gram. The experiments were performed at different rotational speeds lies in range 600-1500 rev/min. The time duration of experiments was kept in range 90-180 minutes. The sand, bottom ash and fly ash slurry concentration was varied from 30 and 60% (wt.). L_{16} (4^2) orthogonal array was used for five input parameters and each of parameter has four levels as listed in Table 4.4. Erosion wear was considered as an output parameter.

Table 4.4: Variable parameters of different experiments

Factors	Levels			
	I	II	III	IV
Speed (rev/min)	600	900	1200	1500
Time (min)	90	120	150	180
Concentration (wt. %)	30	40	50	60
Material	G.C.I.	SS304	SS316L	SDSS2507
Average fineness number (μm)	N1	N2	N3	N4

4.5 EROSION WEAR EXPERIMENTS

4.5.1 Slurry preparation

A fixed amount of water was added with solid particles to obtain desired solid concentration of slurry suspension. Slurry was prepared in cylindrical pot with capacity of 2000 ml and stirred for 30 minutes at 350 rev/min. The solid concentration of slurry was varied from 30 to 60% (by weight). The weighing of solid and liquid was done by using an electron weighing machine having least count of 0.05 kg.

4.5.2 Slurry pot tester

The Erosion wear experiments were performed on erosion pot tester (Model: TR-401) manufactured by Ducom instruments, Bangalore (India). It consists of a cylindrical pot, rotating spindle and screw jack. Digital meter was provided on tester which enables to control

the spindle speed and time duration. Propeller is fixed to prevent the settling of erodents at bottom of pot (120×120 mm) which rotates at same speed as sample specimen. The circulation of water around pot cup removes the heat generated during experiments. Screw jack provided at bottom of pot enables the height adjustment. The circulation of water around pot cup removes the heat generated during experiments. Screw jack provided at bottom of pot enables the height adjustment. The schematic diagram of the erosion wear pot tester is shown in Figure 4.6.

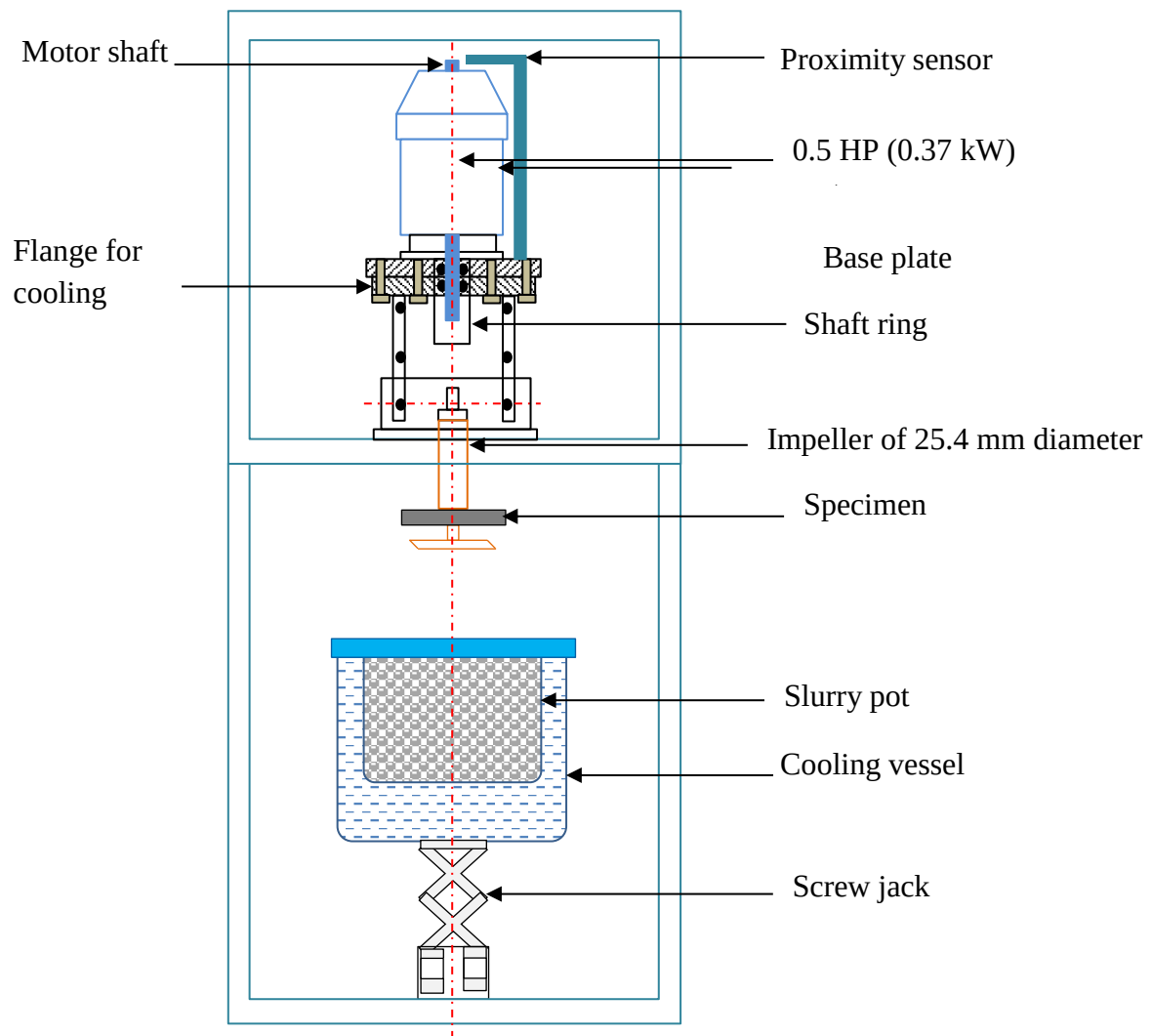


Figure 4.6. Schematic diagram of erosion pot tester.

4.6 EFFECT OF INFLUENCING PARAMETERS ON EROSION WEAR

The erosion wear was found in direct proportion to the velocity of solid moving particles of slurry. Elkholy (1983) had given a correlation which used to determine the values of velocity, diameter and concentration exponents:

$$E_w = k(V)^a(d)^b(C_w)^c \quad (4.1)$$

4.6.1 Signal-to-noise ratio

Signal-to-noise ratio was used to measure the quality characteristics through ANOVA however, the signal indicates the output characteristic and noise is the value of undesirable attributes. The experimental interpretations were transformed in terms of signal-to-noise (S/N) ratios. The S/N ratios were obtained using MINITAB 18 software package. The S/N ratio depends upon the performance characteristics. The most influencing parameter can be determined from the difference between S/N ratios. In present work, S/N ratio is calculated for rotational speed, time duration, solid concentration, average fineness number and material type. The lower-the-better quality rule for calculating the S/N ratio is given as:

$$\frac{S}{N} = -10 \times \log \left[\frac{1}{n} \sum y_i^2 \right] \quad (4.2)$$

Where, 'y' is the erosion wear observations and 'n' is the total observations.

The S/N ratios obtained for erosion wear by sand slurry at different input parameters are listed in Table 4.5. The overall mean of S/N ratios for erosion wear is found as -12.03 dB for sand slurry. The mean effect plot for S/N ratios of erosion wear generated by sand slurry is represented by Figure 4.7. The S/N ratio was found to decrease with increase in erosion wear. It was found that it can be observed that the erosion wear increases with increase in rotational speed, time duration, solid concentration (wt. %) and AFN. However, the order of S/N ratio for erosion wear of different materials was found as: Grey cast iron > SDSS2507 > SS304 > SS316L. The low value of S/N ratio of erosion wear of SS316L shows its minimum erosion wear as compared to SS304, SDSS2507 and grey cast iron. Grey cast iron shows maximum erosion wear among these parameters which may be due to the low microhardness than other materials. Furthermore, the graphite flakes were appeared on the surface of graphite flakes which contributes in ease of plastic deformation at edges of flakes.

Table 4.5: S/N ratios for erosion wear at different input parameters for sand slurry

S. No.	Rotational speed	Time duration	Solid concentration	Materials	Average fineness number	Erosion wear	S/N ratios
1	600	90	30	SS2507	45.6	2.192	-6.818
2	600	120	40	GCI	93.4	3.715	-11.399
3	600	150	50	SS304	121.7	3.391	-10.346
4	600	180	60	SS316L	257.8	2.464	-7.833
5	900	90	40	SS304	257.8	3.343	-10.483
6	900	120	30	SS316L	121.7	1.734	-4.779
7	900	150	60	SS2507	93.4	5.643	-15.030
8	900	180	50	GCI	45.6	5.980	-15.388
9	1200	90	50	SS316L	93.4	2.745	-8.449
10	1200	120	60	SS304	45.6	4.061	-12.173
11	1200	150	30	GCI	257.8	7.365	-17.343
12	1200	180	40	SS2507	121.7	6.899	-16.776
13	1500	90	60	GCI	121.7	6.911	-16.790
14	1500	120	50	SS2507	257.8	7.322	-17.052
15	1500	150	40	SS316L	45.6	2.754	-8.798
16	1500	180	30	SS304	93.4	4.442	-12.952

Table 4.6: S/N ratios for erosion wear at different input parameters for fly ash slurry

S. No.	Rotational speed	Time duration	Solid concentration	Materials	Average fineness number	Erosion wear	S/N ratio
1	600	90	30	SS2507	30.9	2.492	-7.932
2	600	120	40	GCI	89.3	3.955	-11.943
3	600	150	50	SS304	120.4	3.391	-10.606
4	600	180	60	SS316L	184.5	2.564	-8.178
5	900	90	40	SS304	184.5	3.343	-10.483
6	900	120	30	SS316L	120.4	2.234	-6.980
7	900	150	60	SS2507	89.3	5.943	-15.480
8	900	180	50	GCI	30.9	6.480	-16.232
9	1200	90	50	SS316L	89.3	2.945	-9.382
10	1200	120	60	SS304	30.9	4.661	-13.370
11	1200	150	30	GCI	184.5	7.165	-17.104
12	1200	180	40	SS2507	120.4	7.099	-17.024
13	1500	90	60	GCI	120.4	7.111	-16.915
14	1500	120	50	SS2507	184.5	6.922	-16.805
15	1500	150	40	SS316L	30.9	3.254	-10.248
16	1500	180	30	SS304	89.3	4.842	-13.701

Table 4.7: S/N ratios for erosion wear at different input parameters for bottom ash slurry

S. No.	Rotational speed	Time duration	Solid concentration	Materials	Average fineness number	Erosion wear	S/N ratio
1	600	90	30	SS2507	55.3	2.685	-8.578
2	600	120	40	GCI	93.6	3.919	-11.863
3	600	150	50	SS304	134.1	3.372	-10.026
4	600	180	60	SS316L	215.4	3.709	-12.687
5	900	90	40	SS304	215.4	3.660	-12.588
6	900	120	30	SS316L	134.1	1.740	-3.167
7	900	150	60	SS2507	93.6	6.455	-16.198
8	900	180	50	GCI	55.3	7.123	-17.053
9	1200	90	50	SS316L	93.6	2.622	-8.372
10	1200	120	60	SS304	55.3	5.012	-13.999
11	1200	150	30	GCI	215.4	7.644	-17.891
12	1200	180	40	SS2507	134.1	7.661	-17.339
13	1500	90	60	GCI	134.1	7.994	-18.034
14	1500	120	50	SS2507	215.4	6.958	-16.974
15	1500	150	40	SS316L	55.3	3.400	-10.630
16	1500	180	30	SS304	93.6	5.074	-14.108

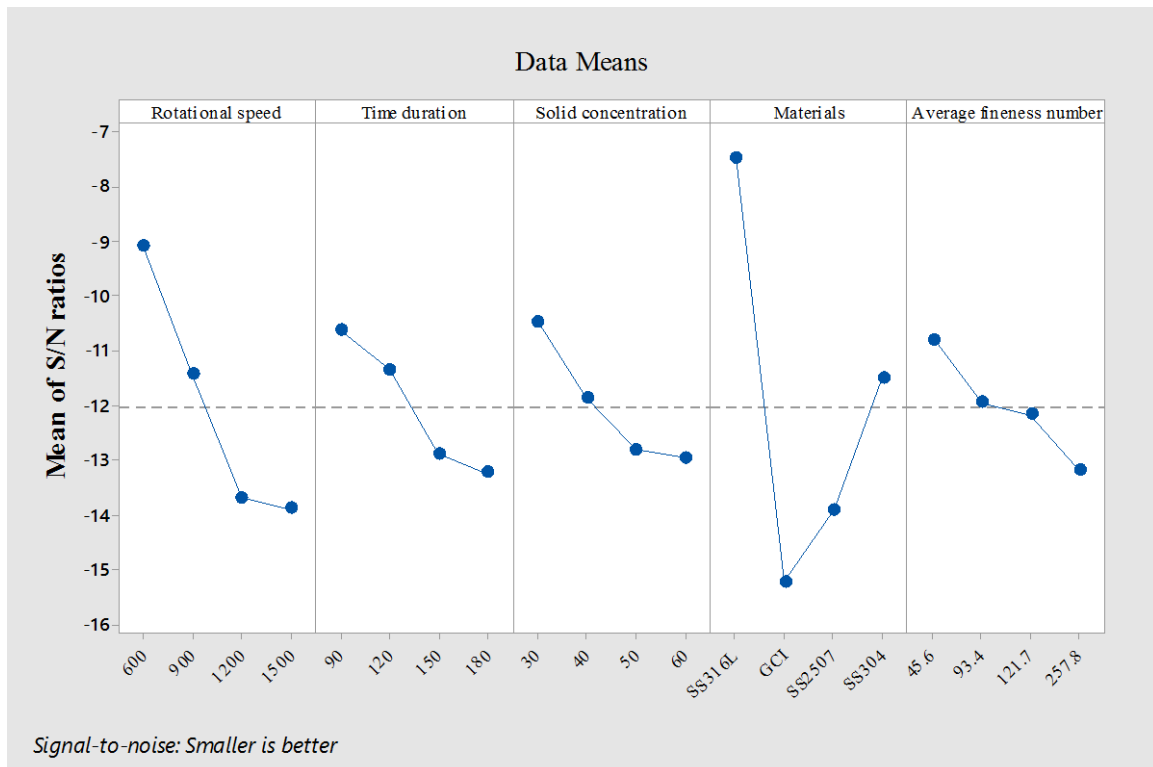


Figure 4.7. Main effect plot for S/N ratios of erosion wear generated by sand slurry.

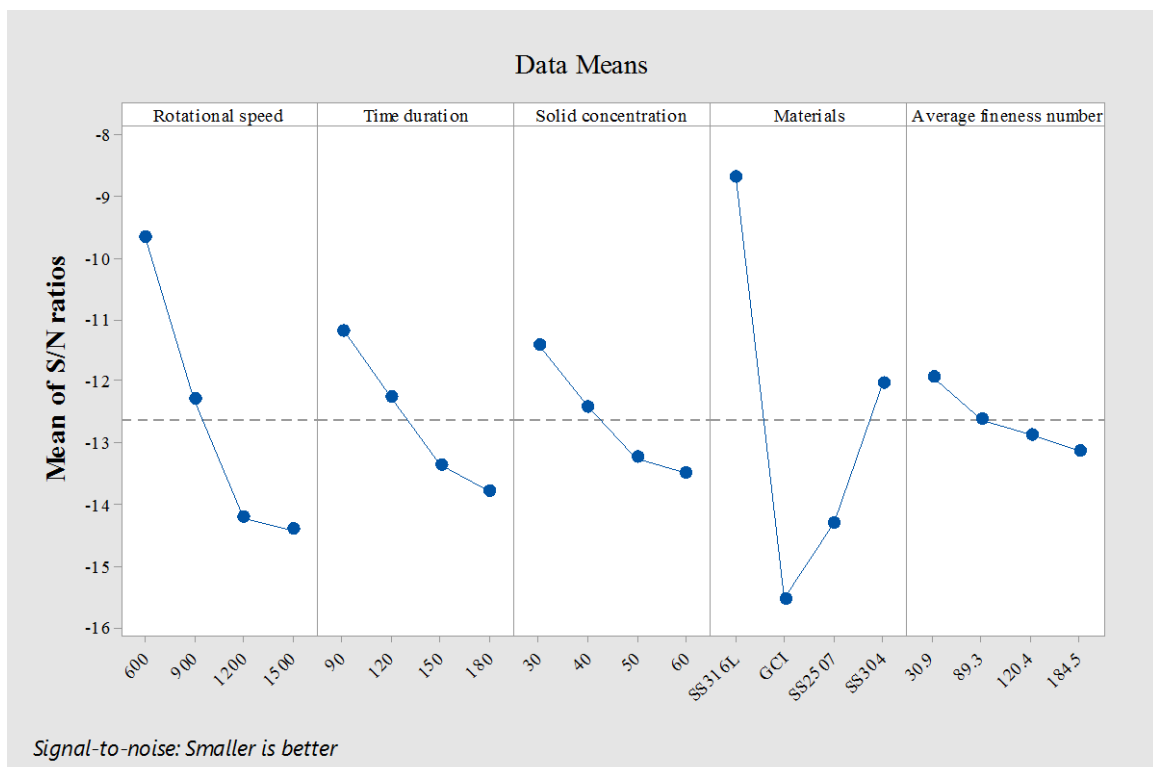


Figure 4.8. Main effect plot for S/N ratios of erosion wear generated by fly slurry.

Figure 4.7 shows the mean effect of S/N ratios of erosion wear generated by fly ash slurry. However, the average fineness number varies in case of fly ash. The average fineness number of fly ash slurry was measured as 30.9, 89.3, 120.4 and 184.5 respectively for particle size range of <75, 75-106, 106-150 and >150 μm respectively. The average fineness number of fly ash particles was quite low as compared to the sand particles. The similar trend was observed for erosion wear by fly ash also. Figure 4.8 represents the S/N ratios obtained for erosion wear generated by fly ash slurry at different input parameters. The overall mean of S/N ratios for erosion wear is found as -12.649 dB. From Table 4.6, the maximum erosion wear was observed as 7.16 gm/m^2 at $N = 1200 \text{ rev/min}$, $T = 150 \text{ min}$, $C_w = 30\%$ and $AFN = 184.5 \mu\text{m}$ for grey cast iron. Minimum erosion wear was found as 2.234 gm/m^2 at $N = 900 \text{ rev/min}$, $T = 120 \text{ min}$, $C_w = 30\%$ and $AFN = 120.4 \mu\text{m}$ for SS316L. This also indicates toward the same trend of erosion wear for materials.

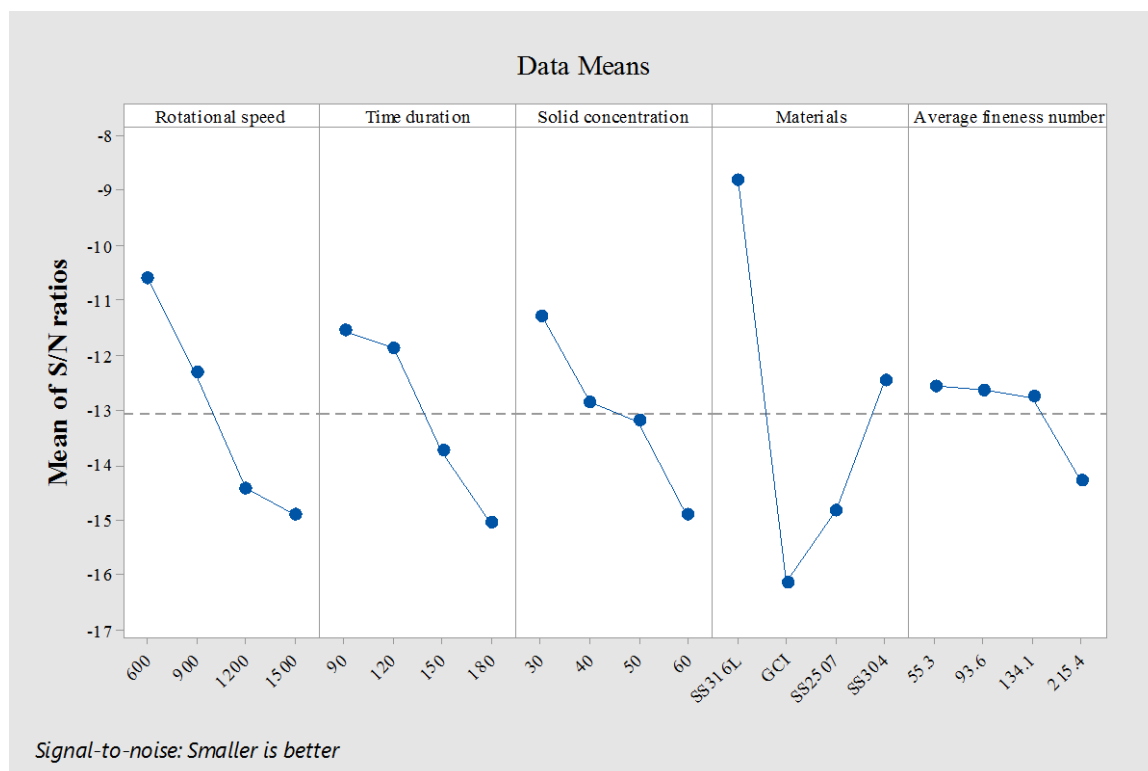


Figure 4.9. Main effect plot for S/N ratios of erosion wear generated by bottom ash slurry.

The S/N ratios of erosion wear for bottom ash slurry are listed in Table 4.7. The average value of S/N ratios for erosion wear by bottom ash slurry was found as -13.094 dB. Similar observation was made for S/N ratios of erosion wear generated by bottom ash slurry. The

maximum erosion wear was observed as 7.994 gm/m² at $N = 1500$ rev/min, $T = 90$ min, $C_w = 60\%$ and $AFN = 134.1$ μm for grey cast iron whereas the minimum erosion wear was found as 1.740 gm/m² at $N = 900$ rev/min, $T = 120$ min, $C_w = 30\%$ and $AFN = 134.1$ μm for SS316L (as shown in Figure 4.9). From mean effect plots, it is very tough to analyze the most influencing parameter due to close values of S/N ratios. Thus, it needs further analysis to reveal the most influencing factor as well as relationship between various parameters.

4.6.2 Response of different parameters

The values of rank and delta were generated on the basis of smaller-the-better characteristic of S/N ratios. The response of different S/N ratios for erosion wear by sand slurry is summarized in Table 4.8. The value of delta in response table of erosion wear by sand slurry was found as 7.765, 4.799, 2.602, 2.483 and 2.383 respectively for material type, rotational speed, solid concentration, time duration and average fineness number (AFN). The higher value of delta represents the higher rank of a particular factor. From results, it can be seen that the rank of material type was highest among rotational speed, time duration, solid concentration (wt. %) and AFN . Among from process parameters the rotational speed was the most influencing factor. The results data validates the statement of researchers (Gandhi et al. 1999; Gupta et al. 1995).

Table 4.8: Response table for S/N ratios for erosion wear by sand slurry

Level	Rotational speed	Time duration	Solid concentration	Materials	Average fineness number
1	-9.099	-10.635	-10.473	-7.465	-10.794
2	-11.420	-11.351	-11.864	-15.230	-11.957
3	-13.685	-12.879	-12.809	-13.919	-12.173
4	-13.898	-13.237	-12.957	-11.489	-13.178
Delta	4.799	2.602	2.483	7.765	2.383
Rank	2	3	4	1	5

Similarly, the value of delta in response table of erosion wear by fly ash slurry was found as 6.851, 4.752, 2.606, 2.057 and 1.197 respectively for material type, rotational speed, solid concentration (wt. %), time duration and AFN , as summarized in Table 4.9. However, the

value of delta in response table of erosion wear by bottom ash slurry was found as 7.360, 4.315, 3.619, 3.489 and 1.727 respectively for material type, rotational speed, solid concentration (wt. %), time duration and AFN, as summarized in Table 4.10. From values of response of material type, it was also found that SS316L had shown minimum erosion wear as compared to SS304, SDSS2507 and grey cast iron.

Table 4.9: Response table for S/N ratios for erosion wear by fly ash slurry

Level	Rotational speed	Time duration	Solid concentration	Materials	Average fineness number
1	-9.665	-11.178	-11.429	-8.697	-11.945
2	-12.294	-12.275	-12.424	-15.548	-12.626
3	-14.220	-13.359	-13.256	-14.310	-12.882
4	-14.417	-13.784	-13.486	-12.040	-13.142
Delta	4.752	2.606	2.057	6.851	1.197
Rank	2	3	4	1	5

Table 4.10: Response table for S/N ratios for erosion wear by bottom ash slurry

Level	Rotational speed	Time duration	Solid concentration	Materials	Average fineness number
1	-10.596	-11.569	-11.291	-8.799	-12.565
2	-12.333	-11.881	-12.862	-16.160	-12.635
3	-14.431	-13.763	-13.208	-14.828	-12.777
4	-14.911	-15.058	-14.909	-12.484	-14.292
Delta	4.315	3.489	3.619	7.360	1.727
Rank	2	3	4	1	5

4.6.3 Interaction between different parameters

The interactions of erosion wear parameters on response are shown in Figure 4.10-4.12. The absence and presence of interaction can be observed from the parallel and nonparallel lines respectively. It seems that significant erosion wear occurred with change in rotational speed with time duration, solid concentration, average fineness number and material type. However,

none of the line is parallel to other line in all figures which indicate the significant interaction between parameters time duration and solid concentration, time & average fineness number and solid concentration & material type. It can also be visualized that blue lines severely intersects all other lines. It implies that the significant erosion wear occurred on maximum values of different influence parameters.

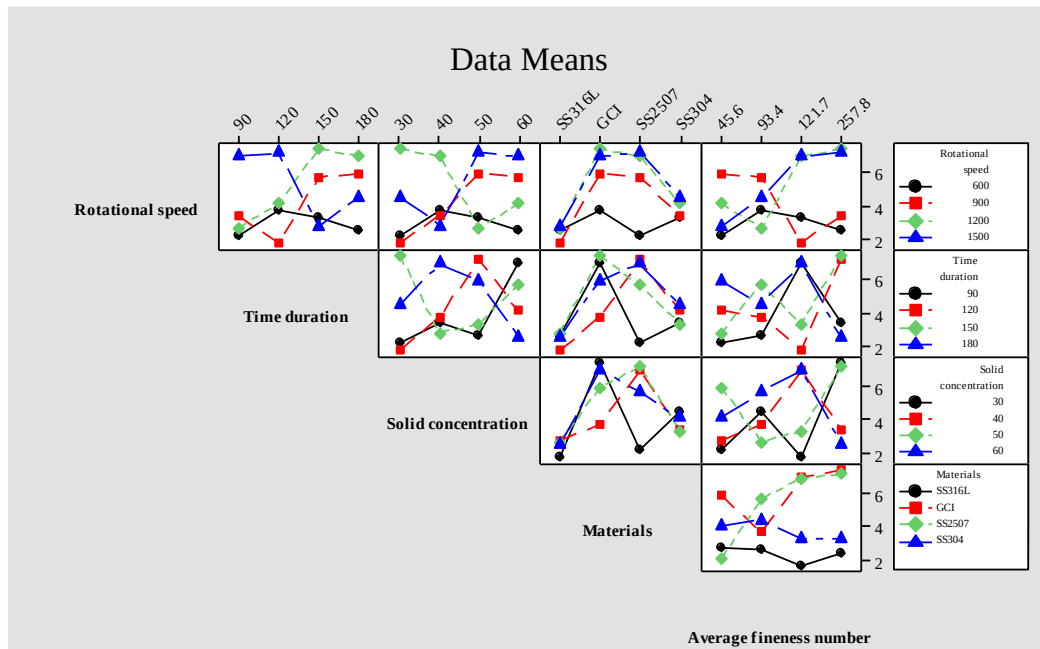


Figure 4.10. Interaction plot between different parameters for erosion wear by sand slurry.

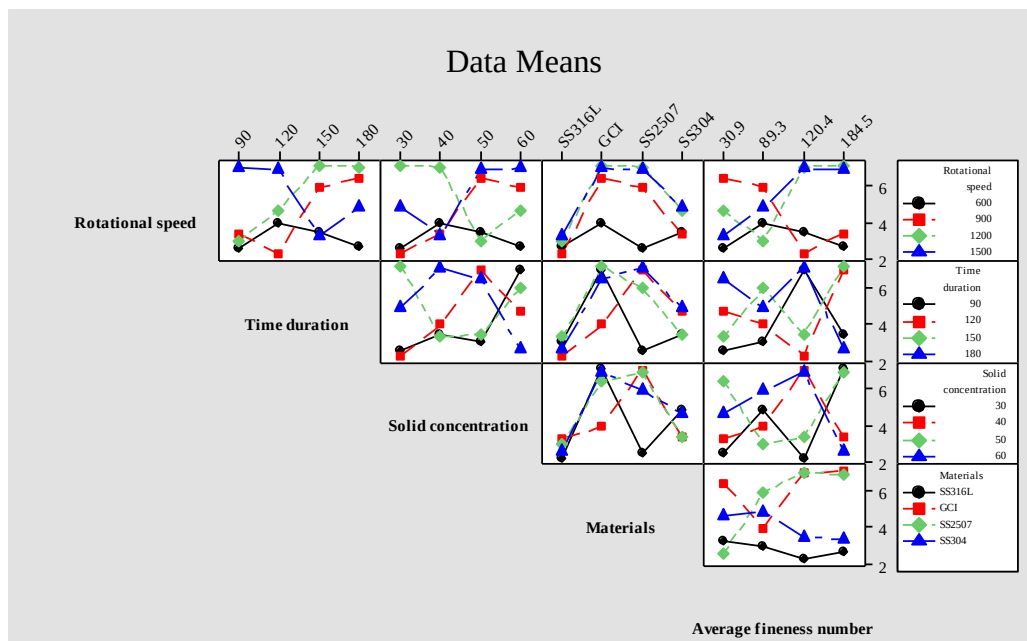


Figure 4.11. Interaction plot between different parameters for erosion wear by fly ash slurry.

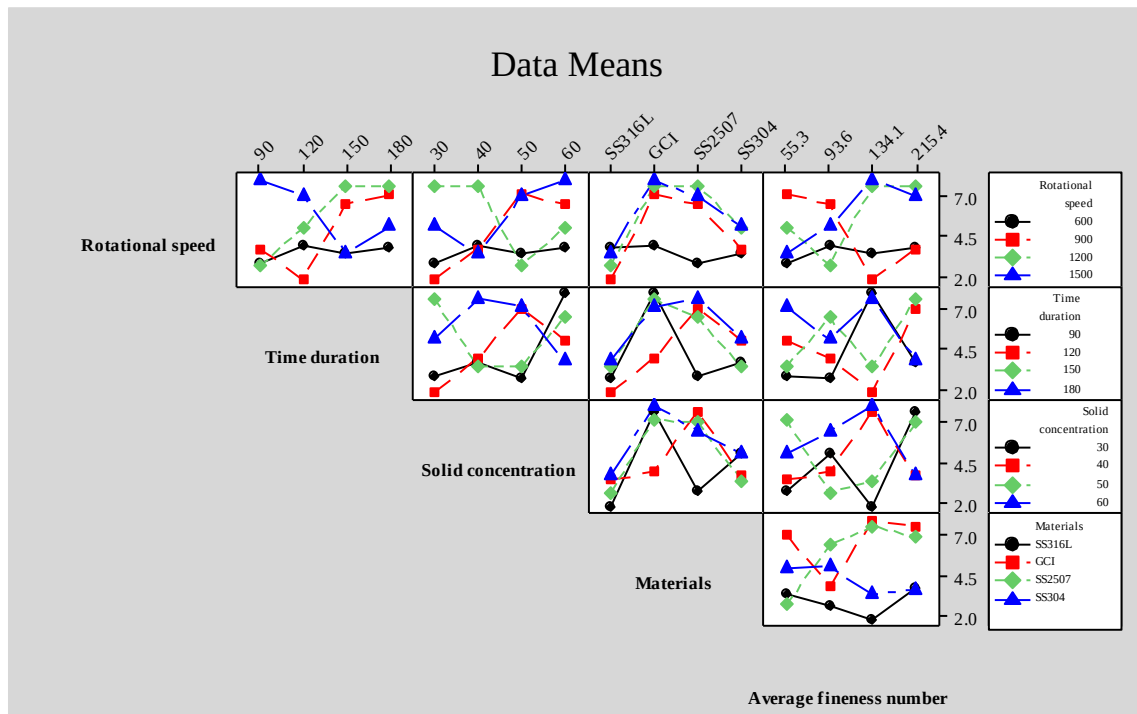


Figure 4.12. Interaction plot between different parameters for erosion wear by bottom ash slurry.

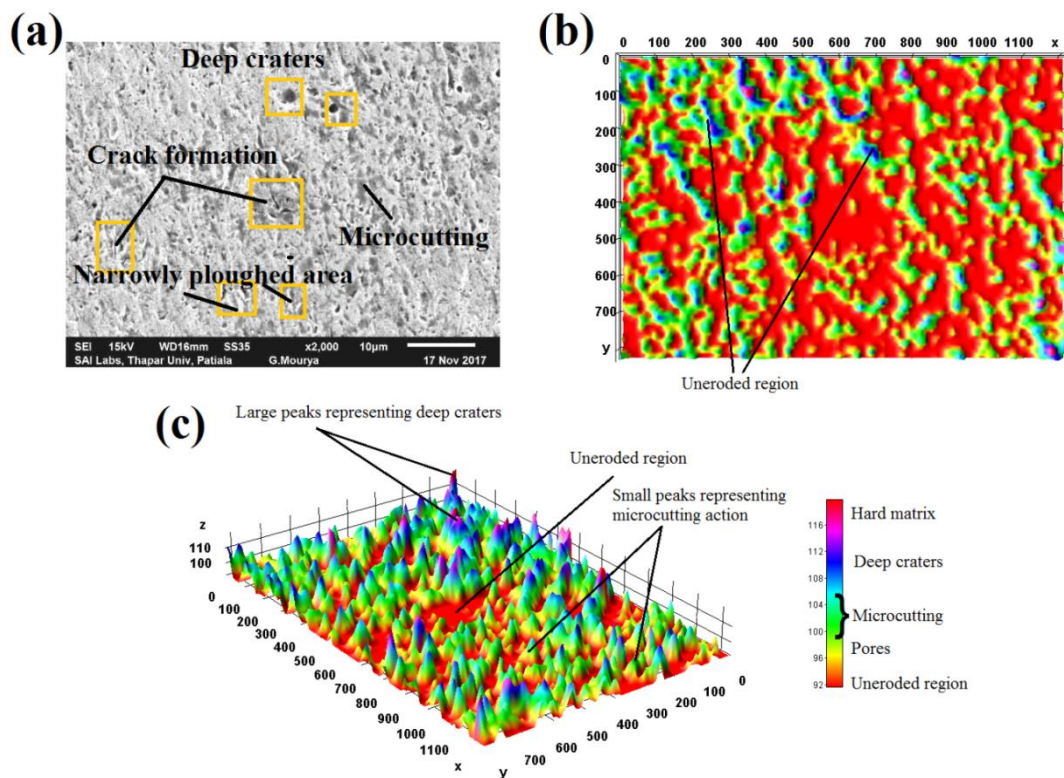


Figure 4.13. Surface morphology & topology of SS316L eroded surface by fly ash slurry.

4.7 MICROSTRUCTURAL ANALYSIS OF ERODED PUMP MATERIALS

An image processing technique was also employed to visualize the erosion wear mechanism more clearly. For the analysis, the scanning electron microscopy was performed for the eroded surfaces (at solid concentration of 30%, rotational speed of 1500 rev/min, impact angle of 0° , time duration of 180 min). 3D surface plots were generated from the SEM images of SS316L that had been eroded by fly ash, bottom ash, and sand. The SEM images of SS316L eroded by fly ash are shown in Figure 4.13 along with 3D and 2D surface plots. As seen in Figure 4.13(a), the erosion wear generated by fly ash resulted in a micro cutting action. In a narrow region, the surface area of the SS316L sample seems to be ploughed and cratered, whereas crack formations were insignificant and negligible. In Figures 4.13(b) and (c), the red regions in the 2D and 3D surface plots indicate the lighter region of SEM images which indicates uneroded areas of the SS316L samples. The large peaks in the 3D plot indicate deep craters formed due to erosion wear, as shown in Figure 4.13(c). Similarly, the surface morphology and topology of SS304 eroded surface by fly ash slurry are shown in Figure 4.14. From Figure 4.14(b), it was observed that smear regions appear after erosion wear process. A large region shows the microcutting action on the surface which is represented by yellow-red peaks on Figure 4.14(c).

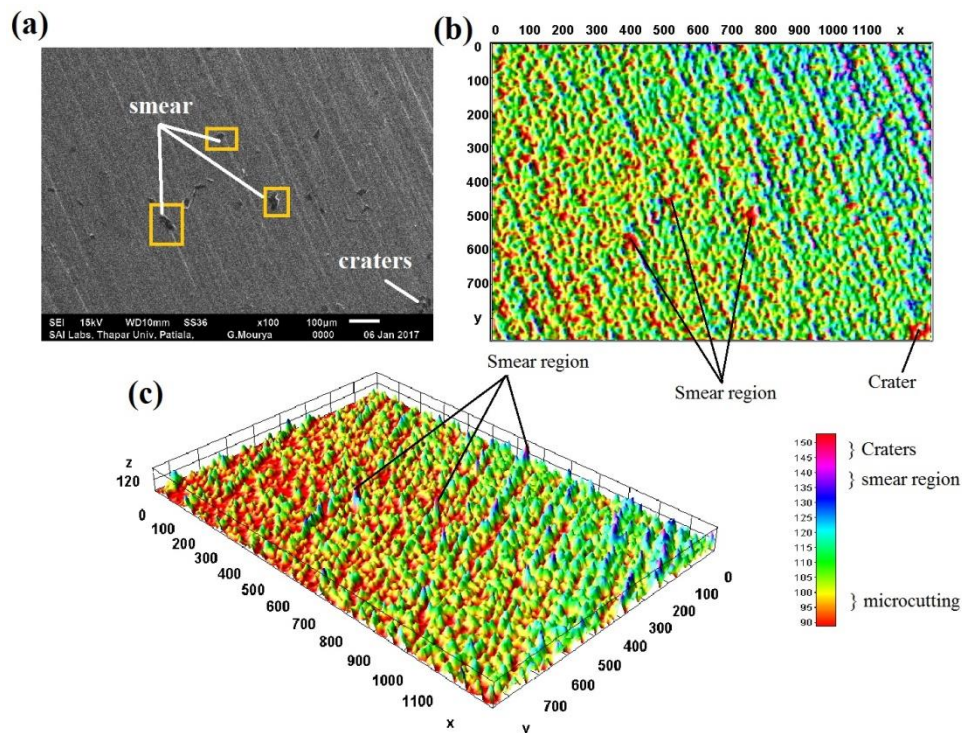


Figure 4.14. Surface morphology & topology of SS304 eroded surface by fly ash slurry.

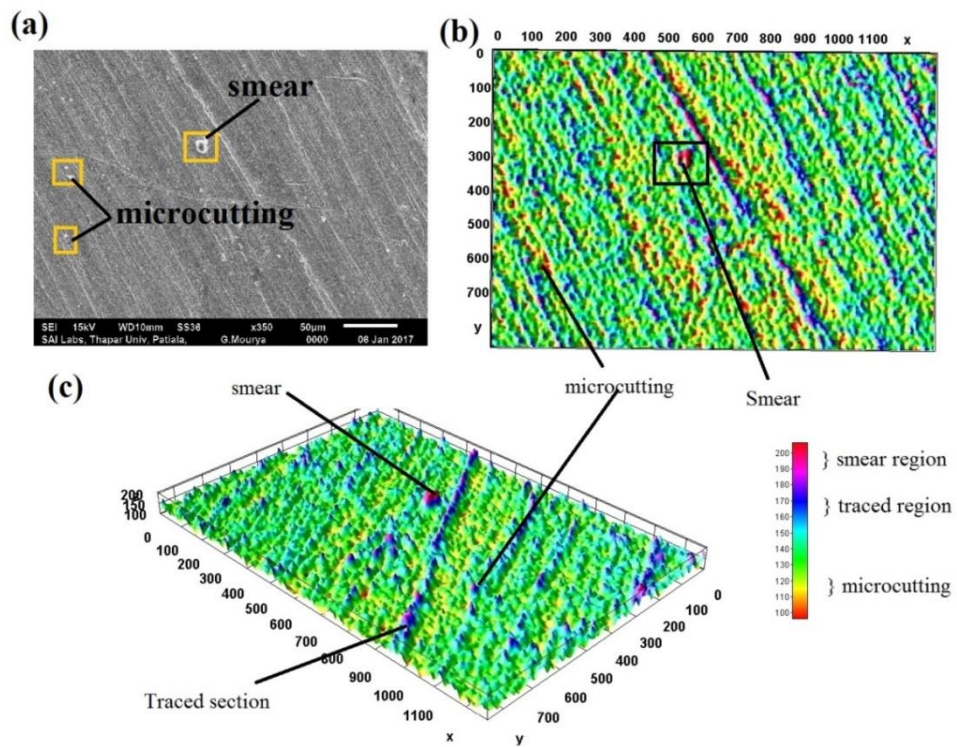


Figure 4.15. Surface morphology & topology of SDSS2507 eroded surface by fly ash slurry.

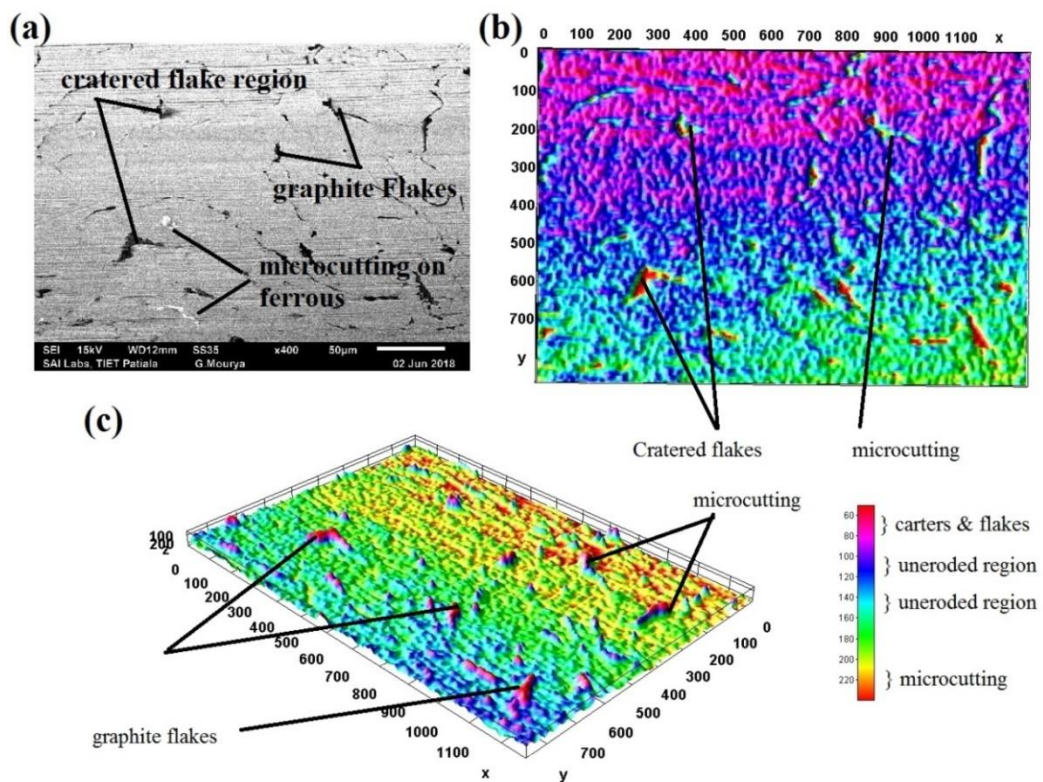


Figure 4.16. Surface morphology & topology of grey cast iron eroded surface by fly ash slurry.

Surface morphology and topology of SDSS2507 eroded surface by fly ash slurry is shown in Figure 4.15. From Figure 4.15(a) and (b), the smear and microcutting action was observed on the surface of SDSS2507. Smear region can be visualized by peaks of violet color in Figure 4.15(c). Few regions were undergone to microcutting actions which can be seen in 2D topographic image. Similarly, the surface morphology & topology of Grey C.I. eroded surface by fly ash slurry is shown in Figure 4.16. Grey cast iron (C.I.) shows different erosion wear behavior as compared to the stainless steels. Grey C.I. contains graphite flakes which were gone through craters as observed from Figure 4.16(b) and (c) also.

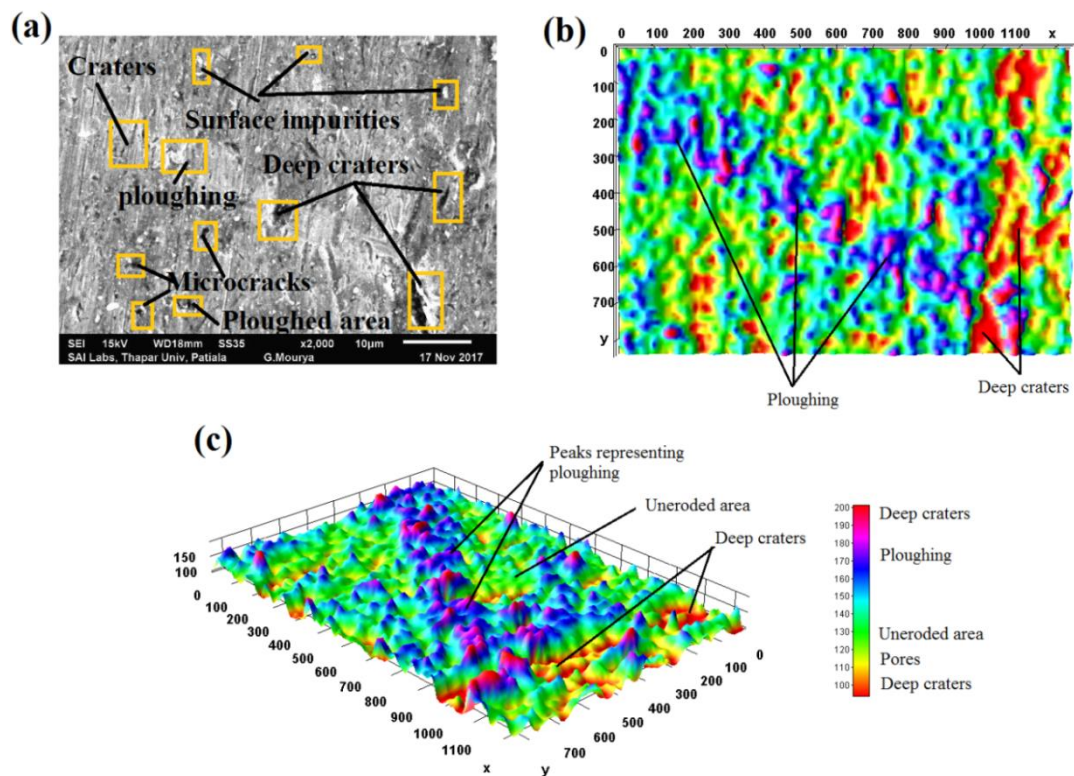


Figure 4.17. Surface morphology & topology of SS316L eroded surface by bottom ash slurry.

Figure 4.17 shows erosion wear due to bottom ash particles on the surface of SS316L. From Figure 4.17(a), it can be seen that craters and ploughing were the major erosion wear mechanisms. Craters were formed throughout the eroded surface. In Figure 4.17(b), the red region indicates the darker region of the SEM image, which represents deep craters generated by bottom ash particles. The ploughed area in the 2D surface plot is indicated by the blue region. The erosion wear mechanism generated by bottom ash particles becomes quite clear from the 3D surface plot, as shown in Figure 4.17(c). The peaks in blue color represent the

ploughed area of SS 316L. In a smaller region, yellow peaks were also seen, which indicates impurities or pores.

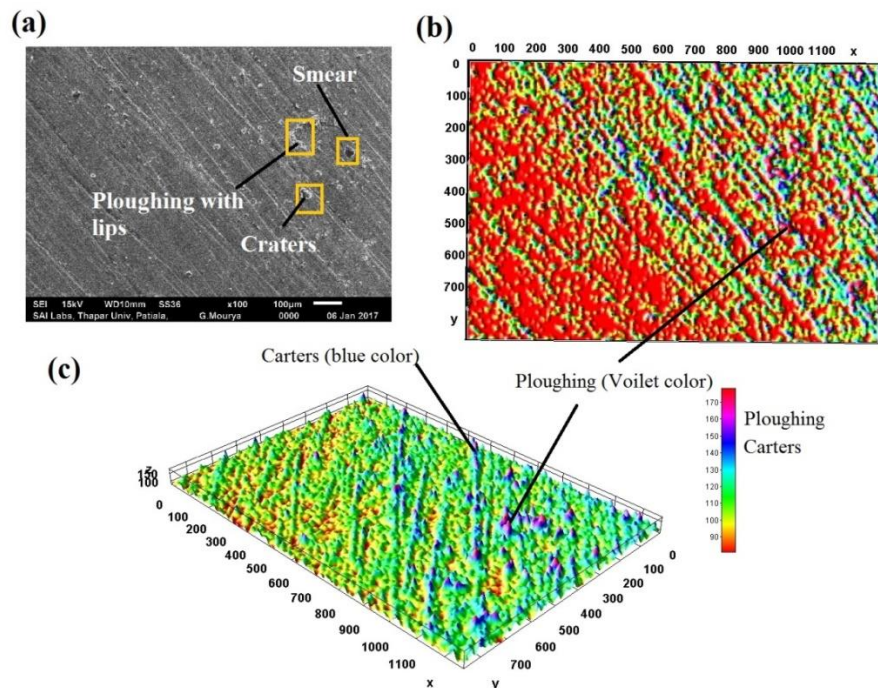


Figure 4.18. Surface morphology & topology of SS304 eroded surface by bottom ash slurry.

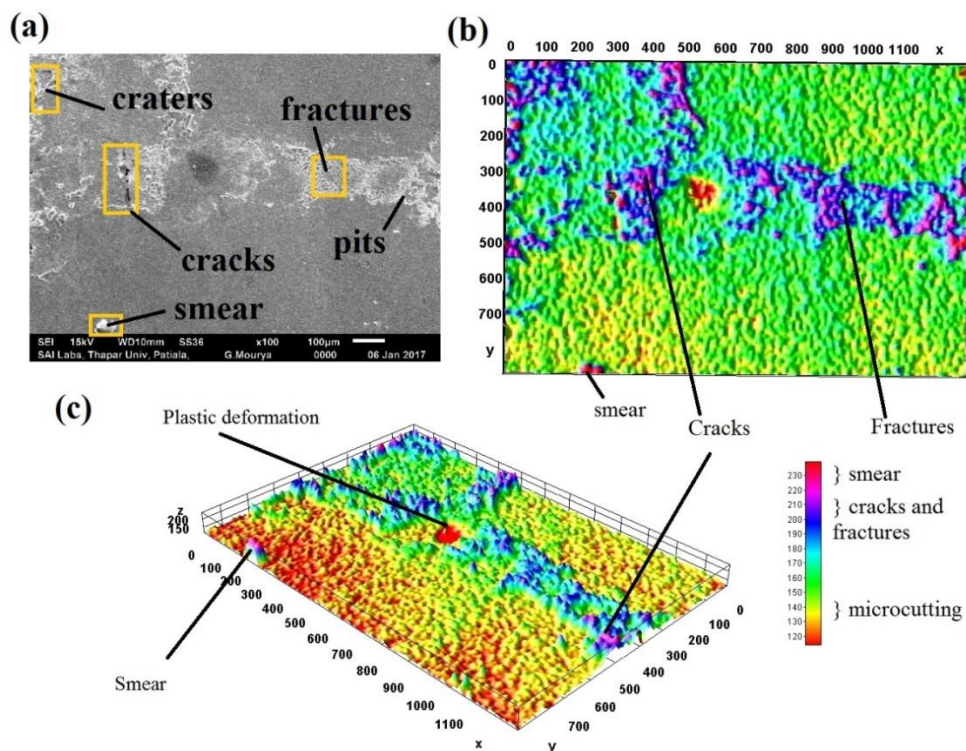


Figure 4.19. Surface morphology & topology of SDSS2507 eroded surface by bottom ash slurry.

Figure 4.18 shows erosion wear due to bottom ash particles on the surface of SS304. SS304 surface under went to ploughing, microcutting and smear mechanisms. Ploughed region can be visualized by violet color in 2D and 3D plots. However, the erosion wear of SDSS2507 due to bottom ash particles is shown by Figure 4.19. From Figure 4.19(c), a large area can be seen which underwent to plastic deformation which is represented by red color. Cracks and fractures were also observed on the eroded surface of SDSS2507. Surface morphology and topology of eroded grey C.I. is represented by Figure 4.20. Smear regions were observed on the eroded surface of grey C. I. From Figure 4.20(c), it can be visualized that the deep craters were seen in flake areas of grey C.I.

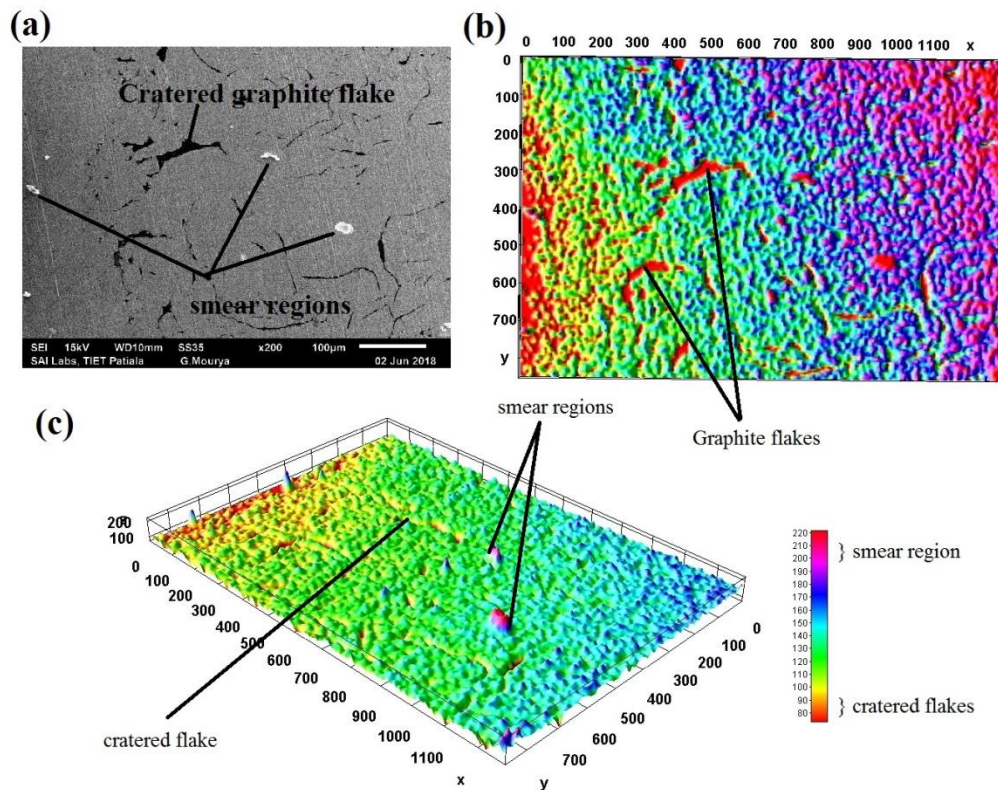


Figure 4.20. Surface morphology & topology of Grey C.I. eroded surface by bottom ash slurry.

Figure 4.21(a) shows the SEM micrograph of a portion of an SS 316L sample eroded by sand particles. From the SEM image, it can be seen that surface cracking and ploughing were major erosion wear mechanisms. The red region in the 2D surface plot indicates the formation of craters, as shown in Figure 4.21(b). The large peaks in Figure 4.21(c) were the major eroded areas of the SS 316L sample (i.e., the dark region in the SEM micrograph image represented by the blue region). Microcutting, fractures, and abrasion are the major

erosion wear mechanisms in centrifugal slurry pumps, as reported by (Elkohly, 1993; Gandhi et al. 1999; Singh et al. 2015; Chowdhury et al. 2016).

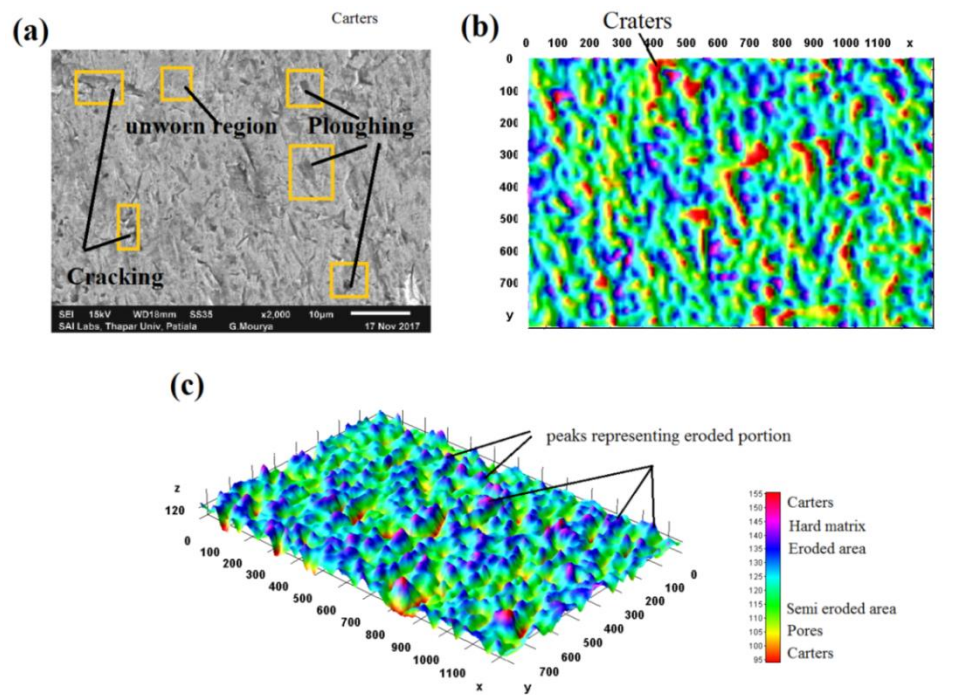


Figure 4.21. Surface morphology & topology of SS316L eroded surface by sand slurry.

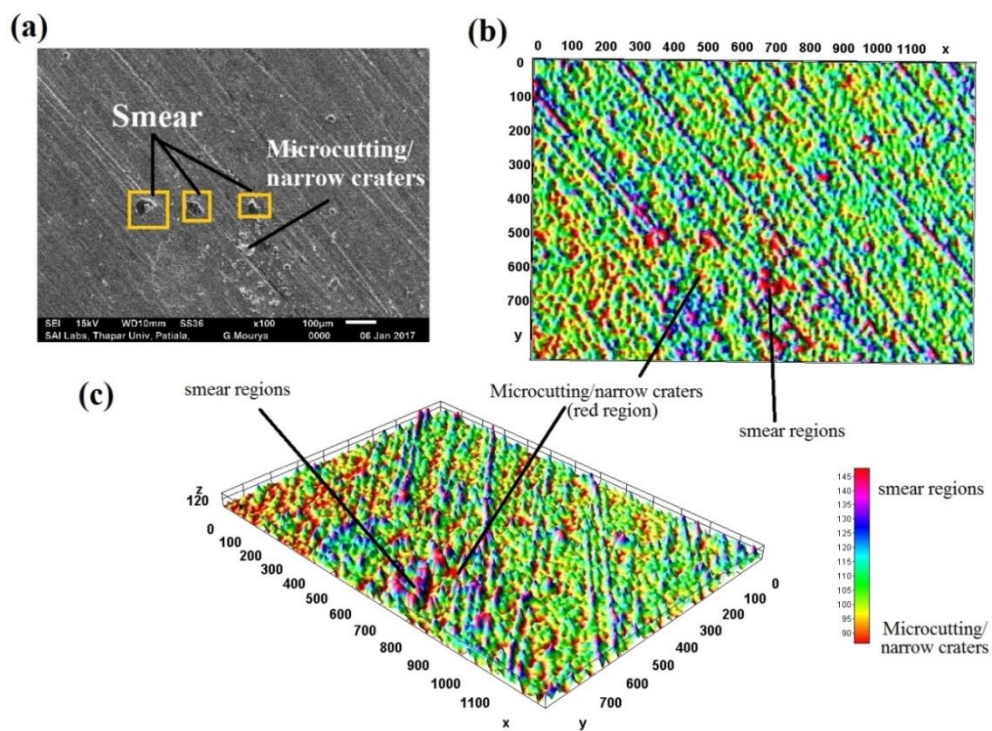


Figure 4.22. Surface morphology & topology of SS304 eroded surface by sand slurry.

Figure 4.22 represents SEM and surface plots of eroded SS304 (by sand slurry). Commonly observed mechanisms were microcutting, narrow craters and smear regions. Figure 4.23 shows the surface morphology of eroded SDSS2507 surface by sand particles. Smear regions and craters can be observed on the surface of SDSS2507, as shown in Figure 4.23 (b) and (c). Microcutting action can be observed by violet peaks in 3D and 2D topographic images.

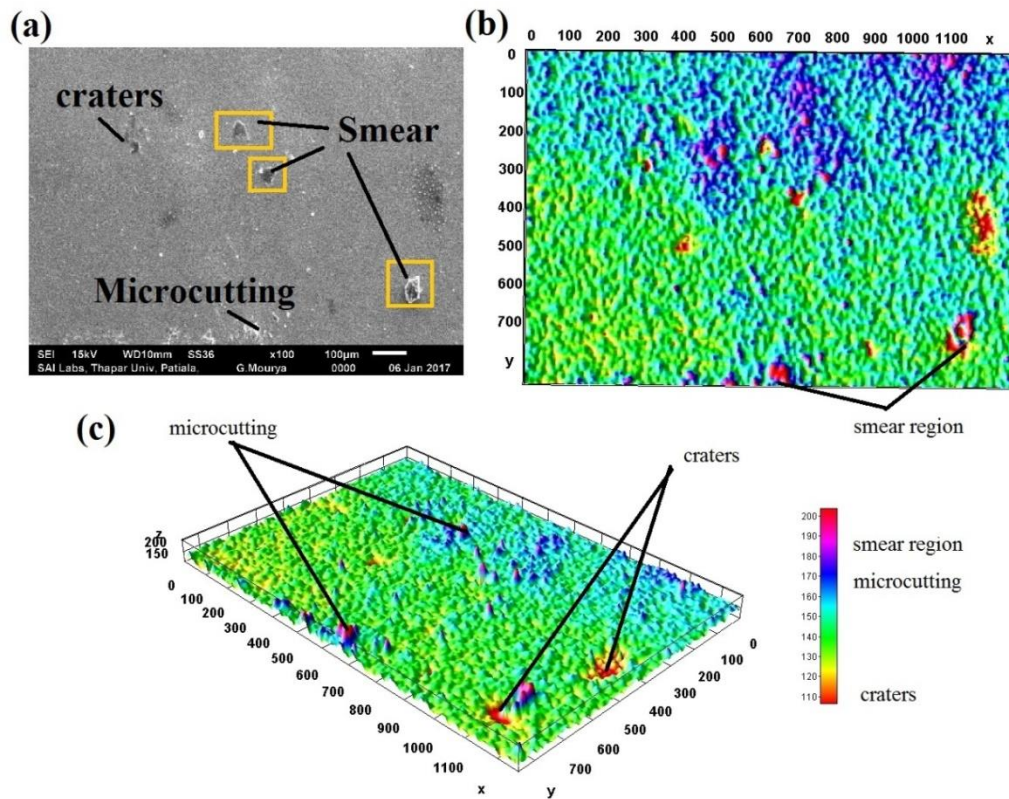


Figure 4.23. Surface morphology & topology of SDSS2507 eroded surface by sand slurry.

4.8 EROSION WEAR MECHANISM IN POT TESTER

Figure 4.24(a) shows the interaction between fly ash particles and the surface of a workpiece specimen. While the fly ash particle strikes the workpiece, it results in the rebounding of the fly ash particles; this rebounding generates plastic deformations on the surface of the workpiece. As shown in Figure 4.24(b), the ploughing action takes place due to the striking of irregularly-shaped bottom ash particles against the surface of the workpiece. As the bottom ash particles continuously collide with the workpiece in the pot tester, they lose their angularity. Similar phenomena occur with sand particles. Sand particles have high angularity

and solidity as compared to bottom ash particles, so chipping action occur due to the continuous collision of sand particles against the workpiece, as shown in Figure 4.24(c).

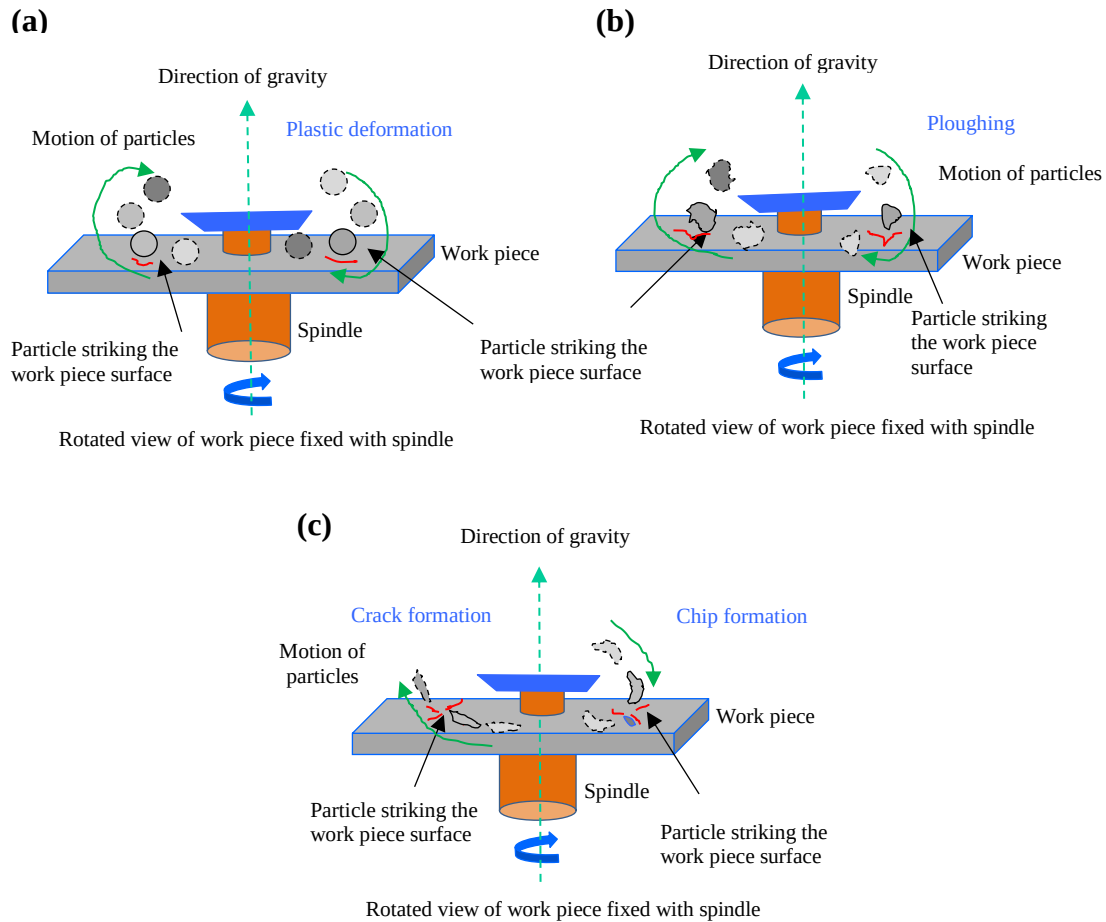


Figure 4.24. Erosion wear mechanism in pot tester due to (a) fly ash (b) bottom ash and (c) sand particles.

4.9 REMARKS

- Average microhardness of the SS304, SS316L, SDSS2507 and grey cast iron for 500 gm load was found as 237, 296, 212 and 207 H.V. respectively.
- The order of S/N ratio for erosion wear of different materials was found as: Grey cast iron > SDSS2507 > SS304 > SS316L.
- Most influencing factor is material type amongst rotational speed, time duration, solid concentration (wt. %) and average fineness number.

CHAPTER 5

EROSION WEAR OF WC-Co-Cr CERMET COATINGS: PART II

EROSION WEAR OF WC-Co-Cr CERMET COATINGS: PART II

5.1 DETAILS OF COATING POWDERS

In present study, different thermal spraying powders were used to enhance the erosion wear resistance to the substrate materials. Generally, commercially available WC–Co, Al and Ni–Cr based coating powders were used to analyze the slurry erosion wear coated pumping materials. Thermal spraying powders namely Y_2O_3 and ZrO_2 powders were purchased from high purity laboratory chemicals (HPLC) Pvt. Ltd. Srigan, (India). WC-10Co4Cr and Mo_2C were purchased from Parshwamani metals, Mumbai (India). The details of thermal spraying powders are mentioned in Table 5.1. The surface morphology was carried out prior from which is shown in Figure 5.1.

Table 5.1: Details of thermal spraying powders

Powder	Grade	Particle size	Base of powder
WC-10Co4Cr	WOKA 3533	$45 \pm 15 \mu m$	WC
Mo_2C	Pure	$< 45 \mu m$	Mo
Y_2O_3	Pure	$< 30 \mu m$	Y
ZrO_2	1% of HfO_2	$< 15 \mu m$	Zr

The specimen used for coating deposition is shown in in Figure 5.2. Test specimens have dimensions of $67.5 \times 25 \times 5$ mm and a concentric hole of 8 mm diameter. Blending of different powders was done by using Jar. The bearing balls used in Jar mill are made of steel and having a diameter of 2 cm.

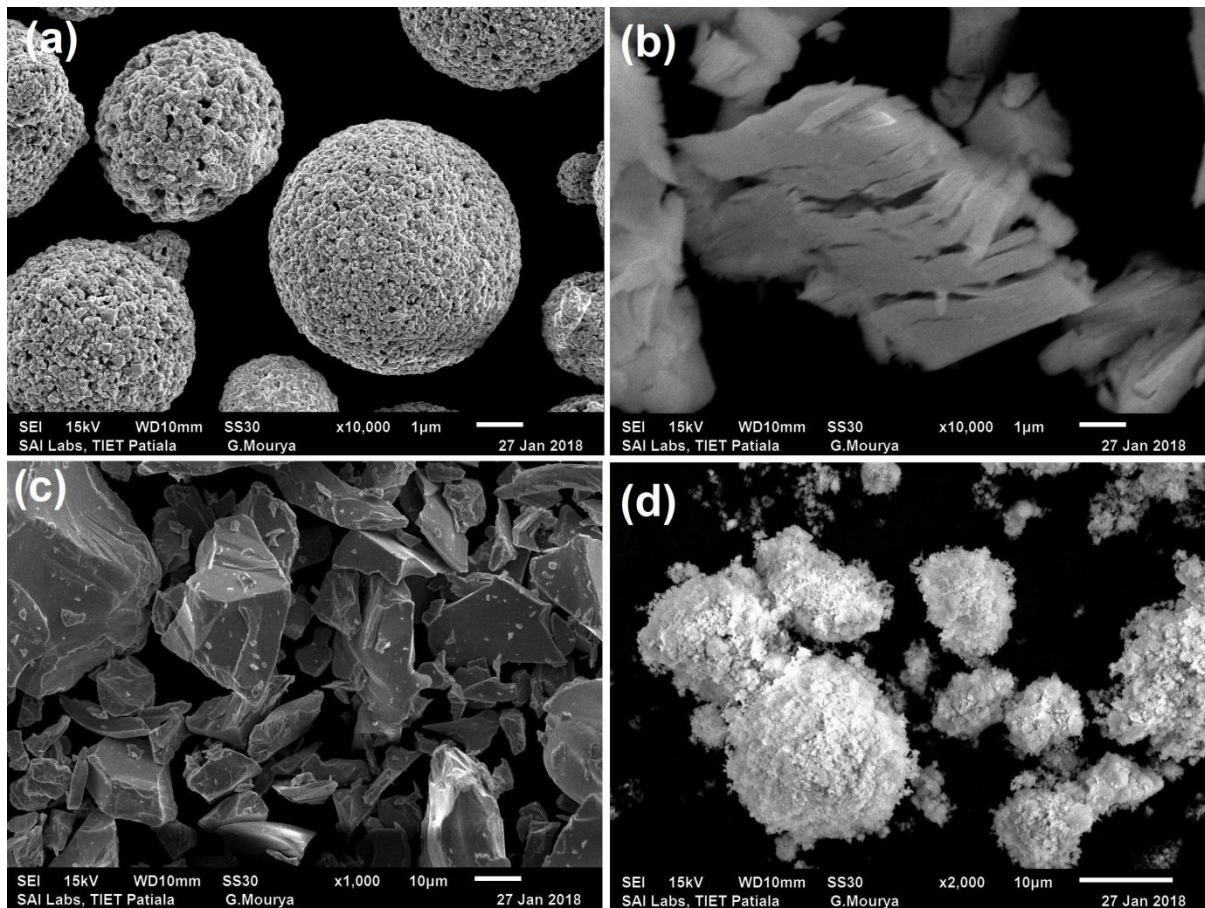


Figure 5.1. Surface morphology of (a) WC-10Co-4Cr, (b) Y₂O₃, (c) Mo₂C, and (d) ZrO₂ coating powders.

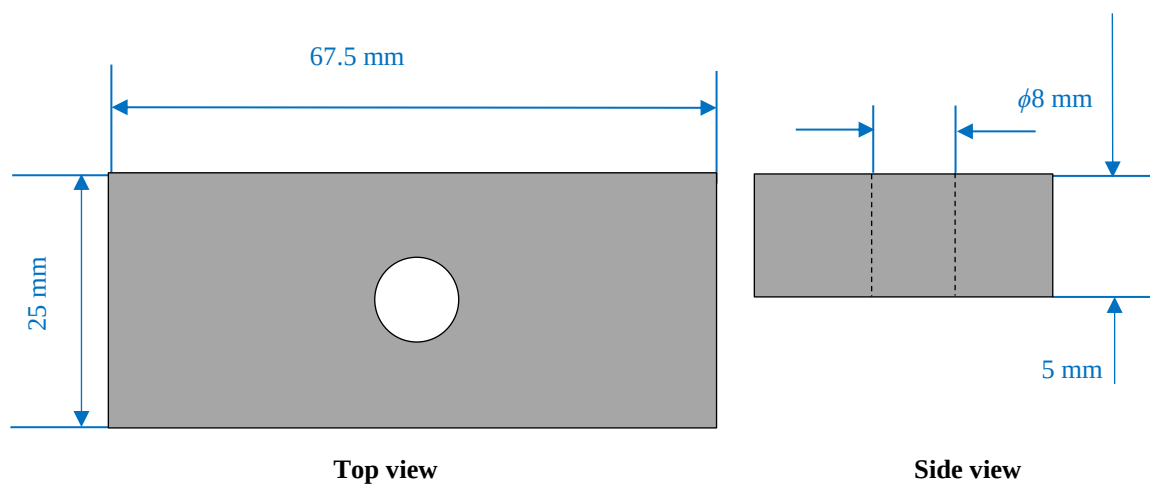


Figure 5.2. Specimen used for coating deposition.



Figure 5.3. Sand blasting unit [Harsha Specialty Welding and Coatings, Panchkula, India].



Figure 5.4. HVOF spraying unit [Harsha Specialty Welding and Coatings, Panchkula, India].

5.2 PREPARATION OF SURFACE

High adhesion strength is essential for long life of coated surfaces. So prior from HVOF spraying, the sand blasting was performed on specimens by using a sand blasting unit (Manufactured by Abrablast Equipment Pvt. Ltd., Jodhpur, India). The sand blasting unit used for present study is shown in Figure 5.3. Sand blasting process provides the random post-collided surface which helps to bind the micron-layer of spraying powder with substrate (i.e. SS-316L/304).

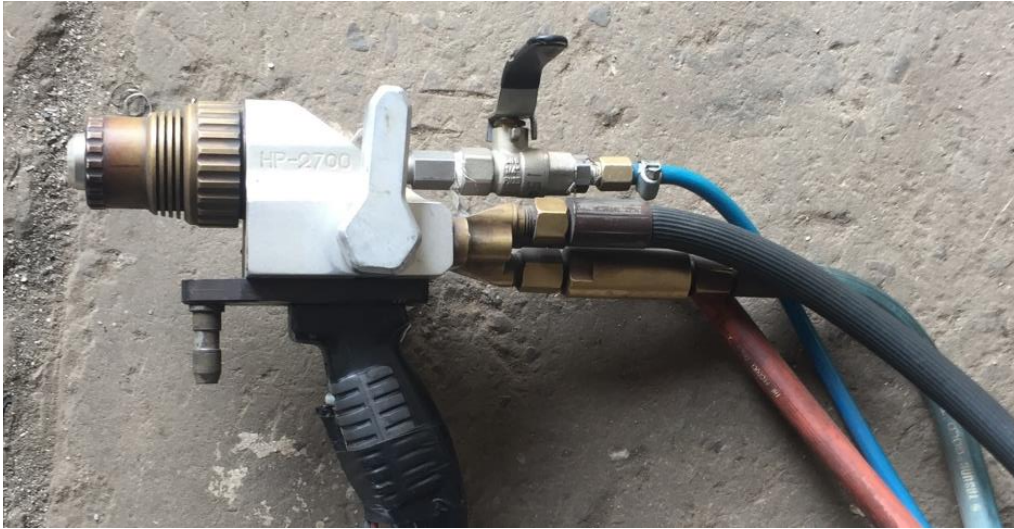


Figure 5.5. Schematic diagram of a typical HVOF torch.

Table 5.2: Spraying parameters during HVOF process

Spray parameter	WC-10Co-4Cr/ WC-10Co4Cr+Mo ₂ C	WC-10Co4Cr+ZrO ₂ WC-10Co4Cr+Y ₂ O ₃
Air flow rate (SPLM)	640	690
Air pressure (kg/cm ³)	6	6
Oxygen flow rate (sLPM)	260	245
Oxygen Pressure (kg/cm ³)	10	10
LPG fuel flow rate (SLPM)	60	70
Fuel pressure (kg/cm ²)	7.5	7.5
Powder feed rate (g/min)	30	25
Spray distance (mm)	150	150

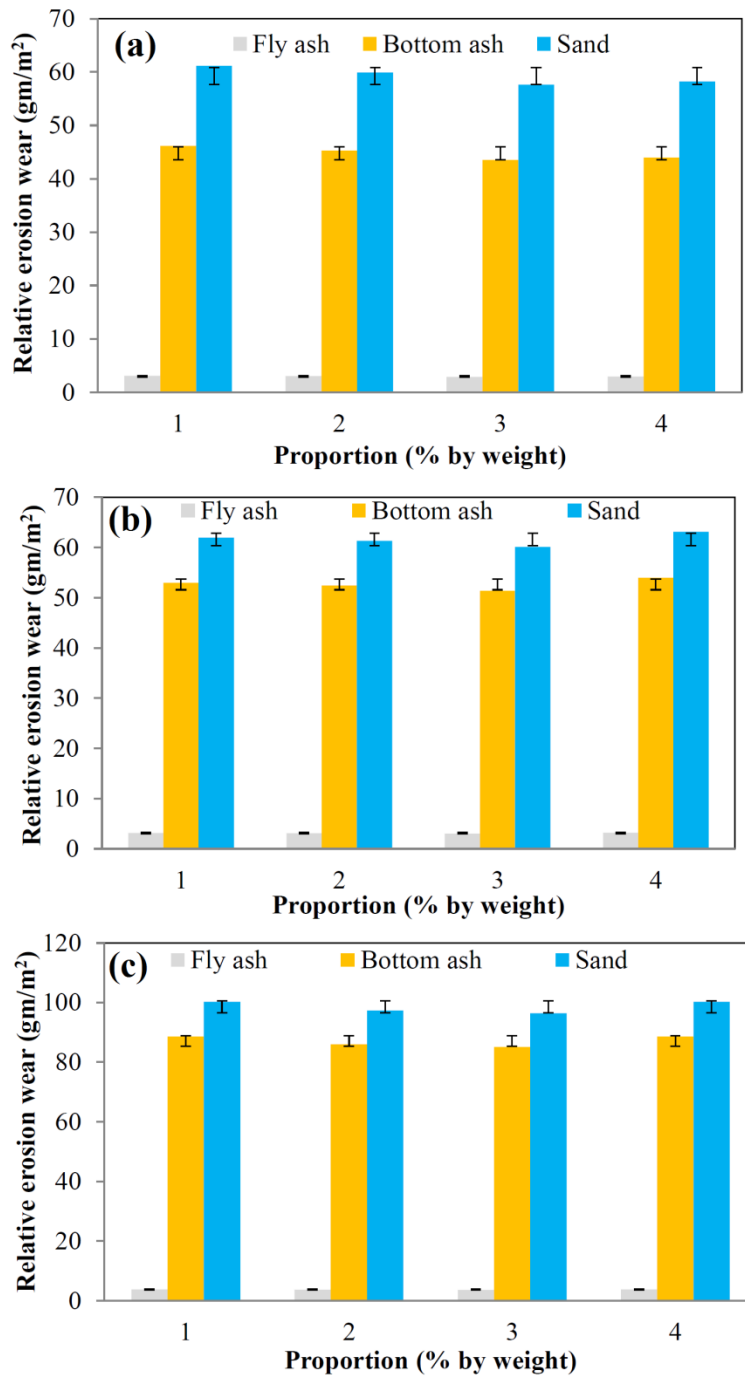


Figure 5.6. Erosion wear results of WC-10Co-4Cr coating with addition of different amounts of (a) Y_2O_3 , (b) Mo_2C , and (c) ZrO_2 powders.

5.3 HVOF SPRAYING PROCESS

HVOF spraying was performed at Harsha Specialty Welding and Coatings Panchkula, India using a HVOF MP-2100 unit and HP-2700 torch. The schematic diagram of HVOF spraying unit and spraying torch is shown in Figure 5.4 and 5.5 respectively. The values of spraying

parameters during HVOF process are mentioned in Table 5.2. Initially, the different weight proportions of different spraying powders were added in WC-Co-Cr coating powder for the purpose of optimization of weight proportion. Coating powders namely Y_2O_3 , Mo_2C , and ZrO_2 were added in proportion of 1%, 2%, 3% and 4% in WC-10Co-4Cr powder. The erosion wear experiments were performed at maximum rotation speed i.e. 1500 rev/min, solid concentration of 30% for the time duration of 180 minutes. The erosion wear results of WC-10Co-4Cr coating with addition of different amounts of different coating powders are shown in Figure 5.6. It was found that the erosion wear was found minimum with 3% addition of different coating powders.

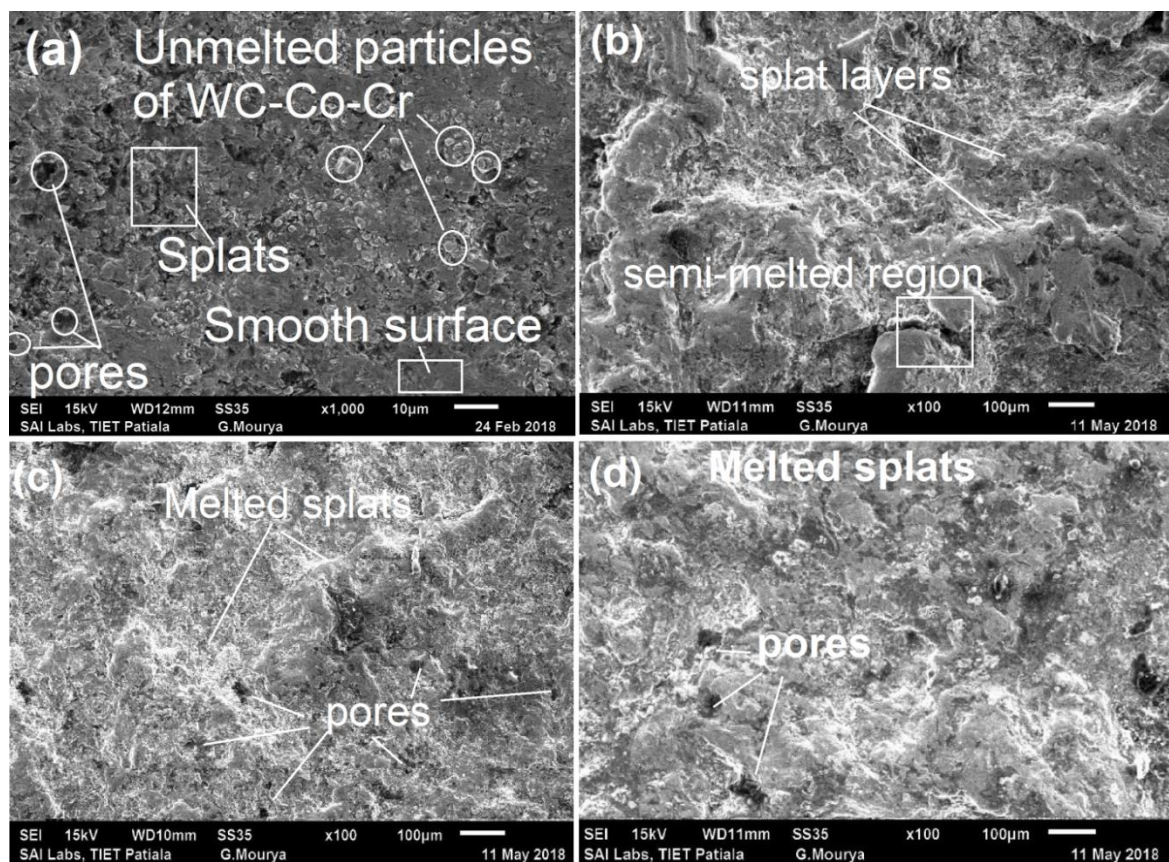


Figure 5.7. SEM micrographs of (a) WC-10Co-4Cr, (b) WC-10Co-4Cr+3% Y_2O_3 , (c) WC-10Co-4Cr+3% Mo_2C , and (d) WC-10Co-4Cr+3% ZrO_2 coatings.

5.4 PRE-EXPERIMENTAL ANALYSIS

5.4.1 Surface morphology of as-sprayed surface

Scanning electron microscopy (SEM) technique was also employed to analyze the surface morphology of as-sprayed surface on surface of substrate. SEM micrographs of WC-10Co-

4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings are shown in Figure 5.7. The SEM images of the HVOF sprayed WC-10Co-4Cr. Figure 5.7(a) indicates the presence of splates, pores and unmelted particles on WC-10Co-4Cr as-sprayed surface. Semi-melted regions were observed on the HVOF sprayed surface of WC-10Co-4Cr+3%Y₂O₃, as shown in Figure 5.7(b). Figure 5.7(c) and (d) represents the clear visualization of melted lamellae splats and pores on HVOF sprayed surface of WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings. Coating thickness was also determined by performing SEM on a cross-sectional area of HVOF coated SS-316L. The coating thickness was measured as a random measure of peaks and valleys which was lies in range 155-185 μ m.

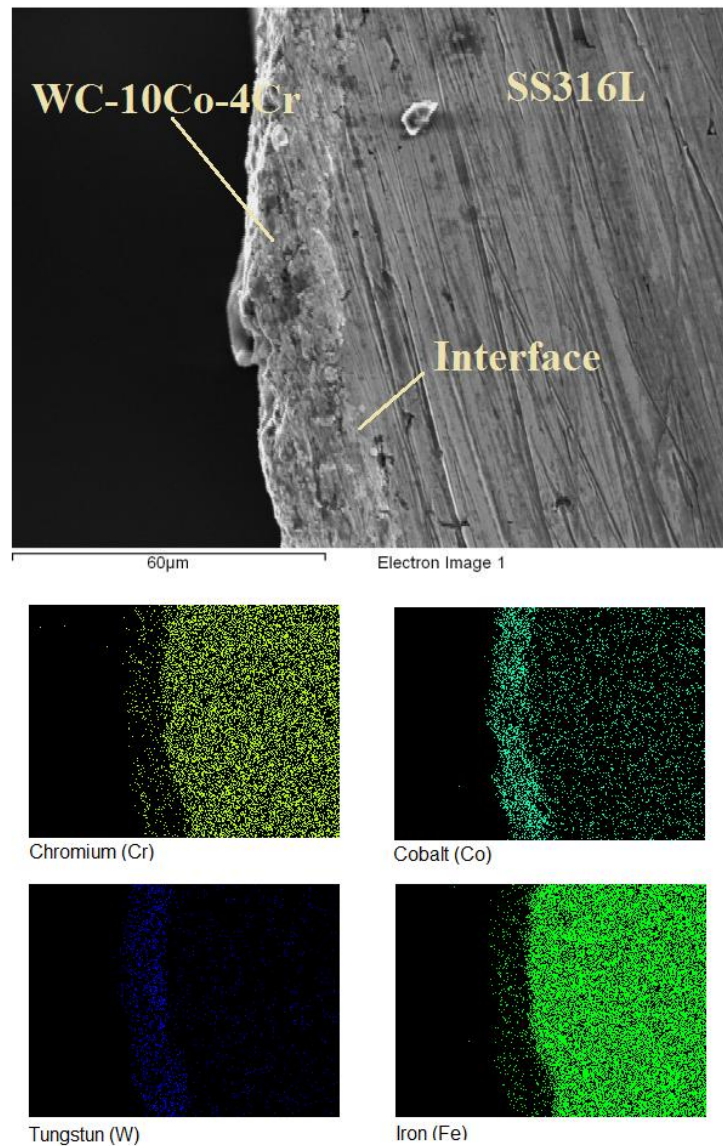


Figure 5.8. EDS map of WC-10Co-4Cr coatings.

The cross-sectional SEM micrograph and EDS maps of WC-10Co-4Cr coating is shown in Figure 5.8. From Figure 5.8, it was observed that a continuous contact occurs between coating and substrate material at interface which implies the uniform coating throughout the surface. The microstructure of coated surface indicates interlocked-splats. Dark gray pattern in micrograph represents the existence of Cr binders in matrix and bright Pattern represents the existence of WC in large amount due to decarburization. Similar observation also made by researchers (Stewart et al. 2000; Sudaprasert et al. 2003). EDS maps of WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coated specimen is shown in Figure 5.9-5.11.

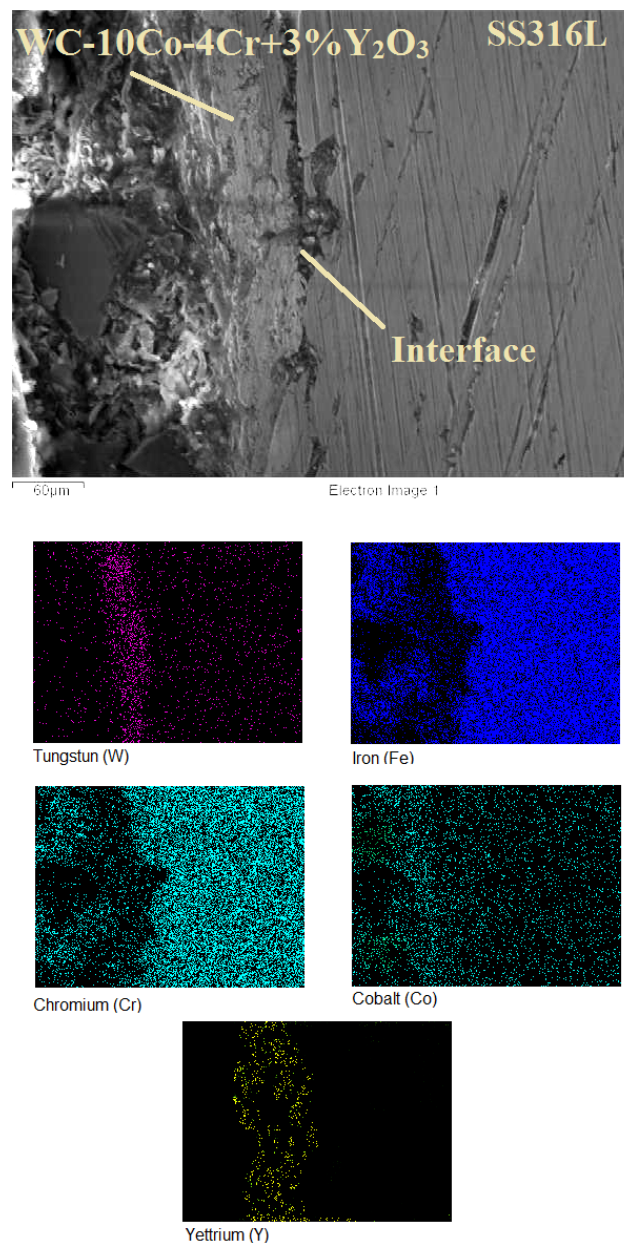
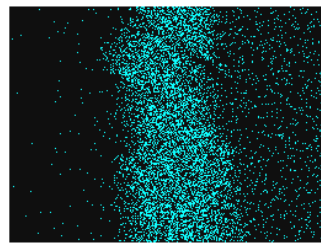
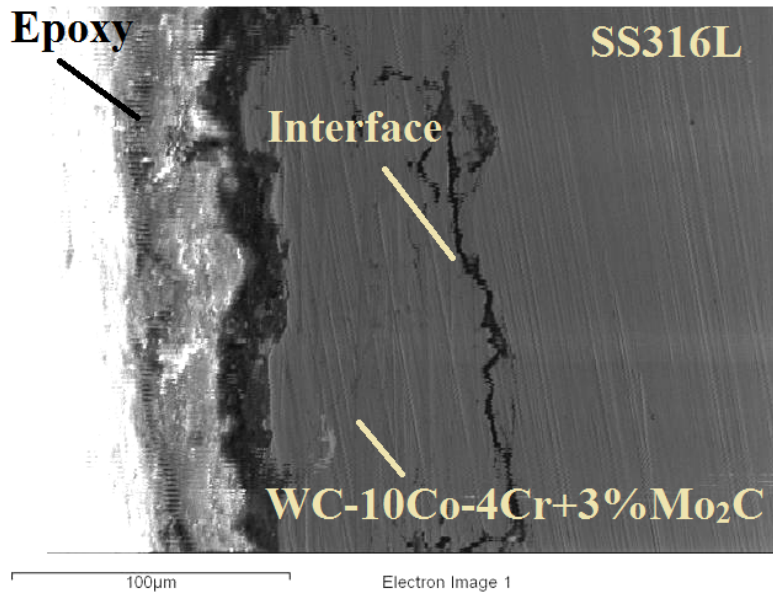
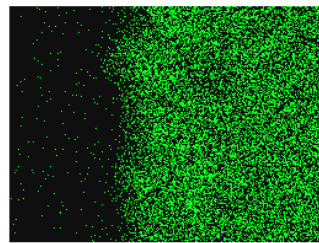


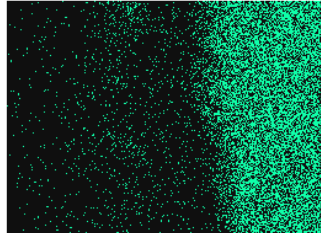
Figure 5.9. EDS map of WC-10Co-4Cr+3%Y₂O₃ coatings.



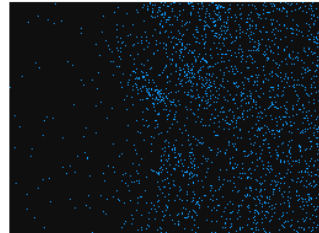
Tungsten (W)



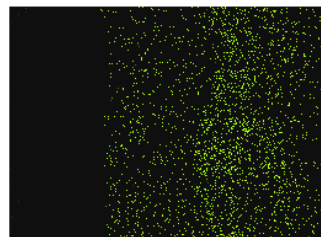
Chromium (Cr)



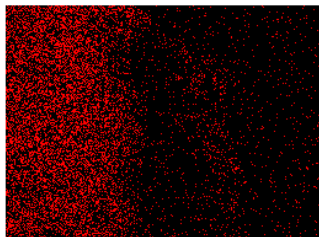
Iron (Fe)



Cobalt (Co)



Molybdenum (Mo)



Carbon (C)

Figure 5.10. EDS map of WC-10Co-4Cr+3%Mo₂C coatings.

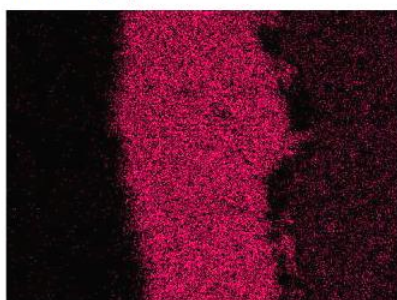
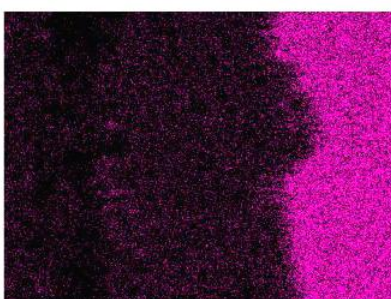
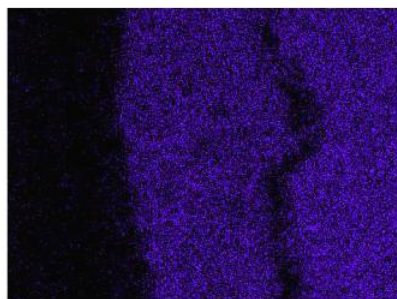
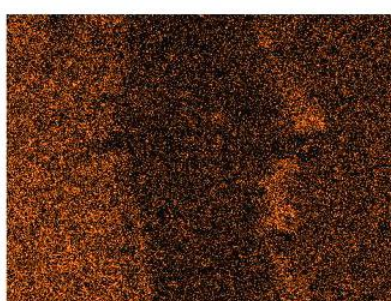
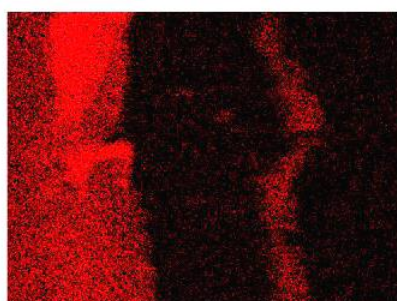
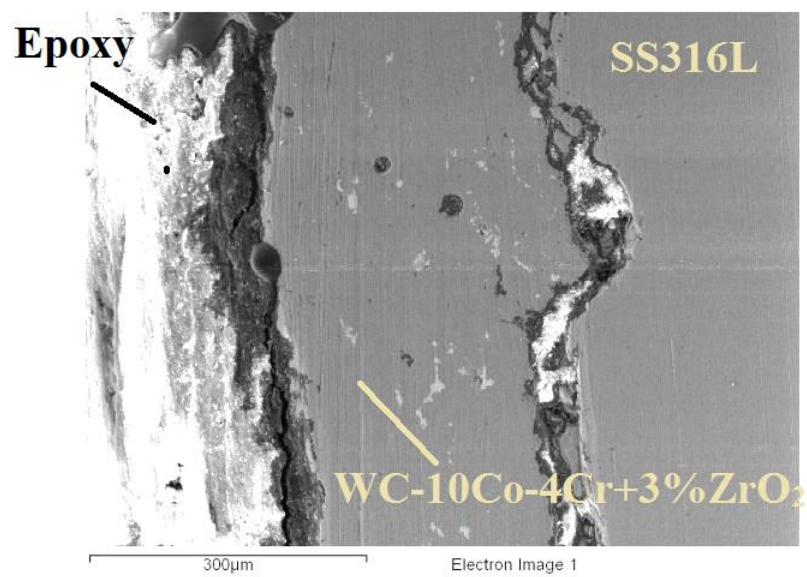


Figure 5.11. EDS map of WC-10Co-4Cr+3%ZrO₂ coatings.

5.4.2 XRD of as-sprayed surface

X-ray diffractions (XRD) were performed using a Philips X'pert diffractometer (Model: PW-1710). The XRD results reveal that crystalline phase WC, W_2C , $Cr_{26}C_6$, Cr_7C_3 , and CoC were present in the WC-10Co-4Cr-coated surface, as shown in Figure 5.12. The WC phase present in the WC-10Co-4Cr coating is generally ductile and undergoes cracks, craters, and fractures. The XRD of WC-10Co-4Cr +3% Y_2O_3 shows the presence of crystalline phases WC, Co_6W_6C , Cr_7C_3 and Y_2O_3 in coated surface, as shown in Figure 5.13. The XRD of WC-10Co-4Cr +3% Mo_2C indicates the presence of WC, W_2C , $\alpha-Mo_2C$, $Cr_{26}C_6$, Cr_7C_3 , and CoC crystalline phases, as shown in Figure 5.14. Figure 5.15 indicates the presence of WC, $W_{32}O_{84}$, W_2C , $\alpha-Mo_2C$, $Cr_{23}C_6$, Cr_3C_7 , CoC, Co_2O_4 (cobalt dicobalt (III) oxide), $\alpha-ZrO_2$, $\beta-ZrO_2$ (baddeleyite), and $\gamma-ZrO_2$ (zirconia nanocrystalline) crystalline phases in XRD results of WC-10Co-4Cr +3% ZrO_2 .

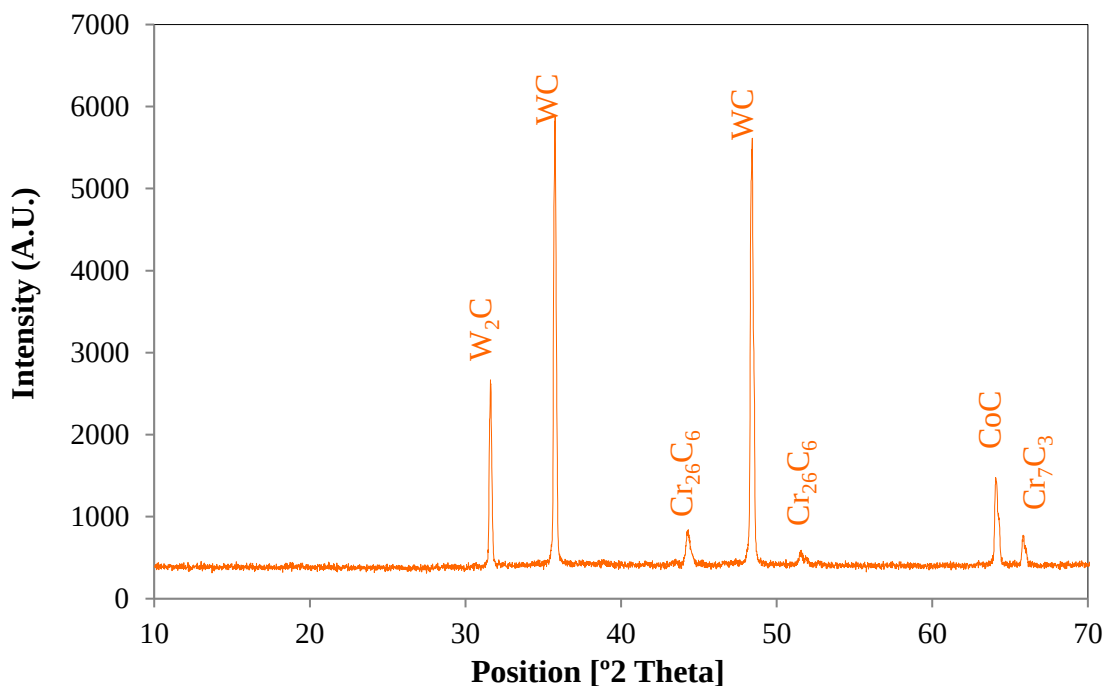


Figure 5.12. XRD spectrums of WC-10Co-4Cr coatings.

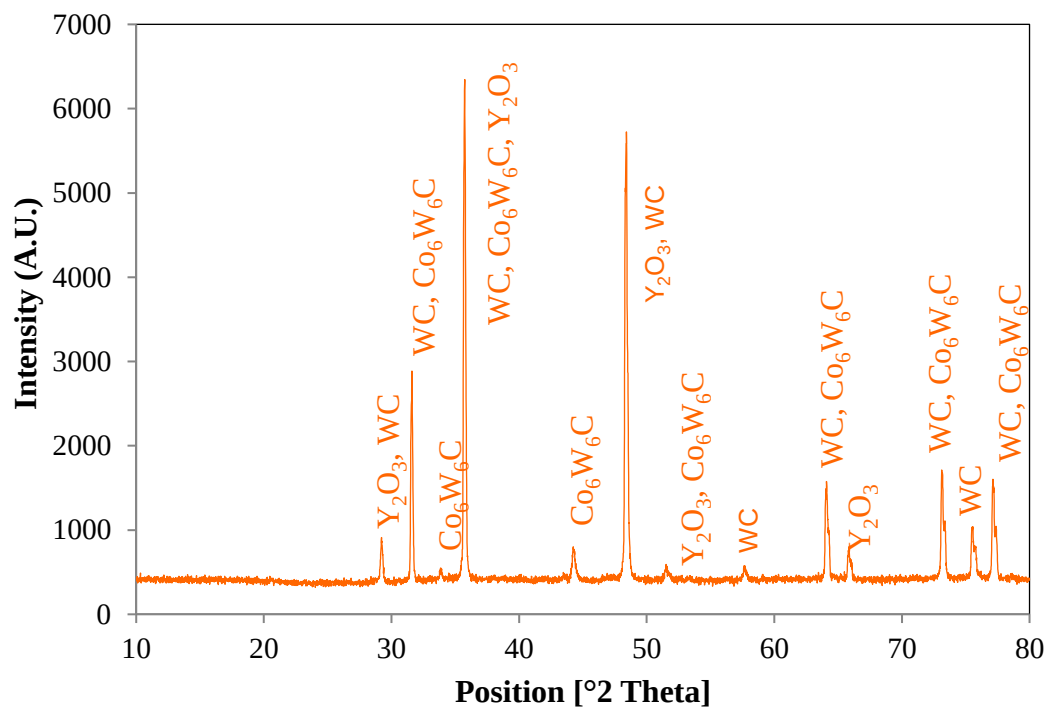


Figure 5.13. XRD spectrums of WC-10Co-4Cr+3% Y_2O_3 coatings.

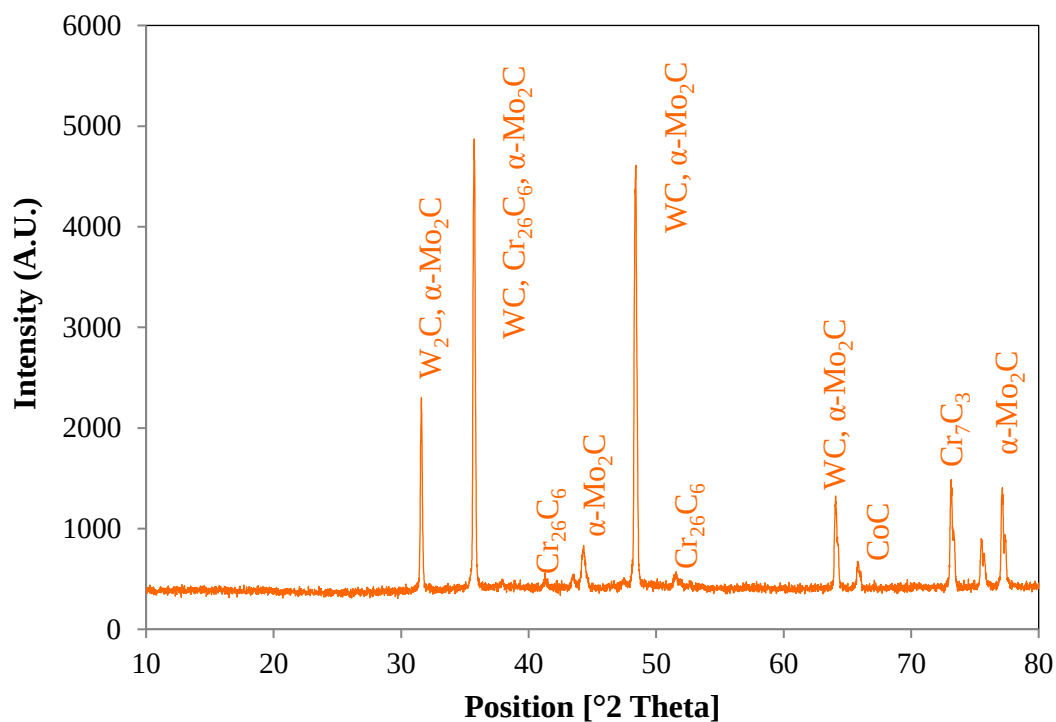


Figure 5.14. XRD spectrums of WC-10Co-4Cr+3% Mo_2C coatings.

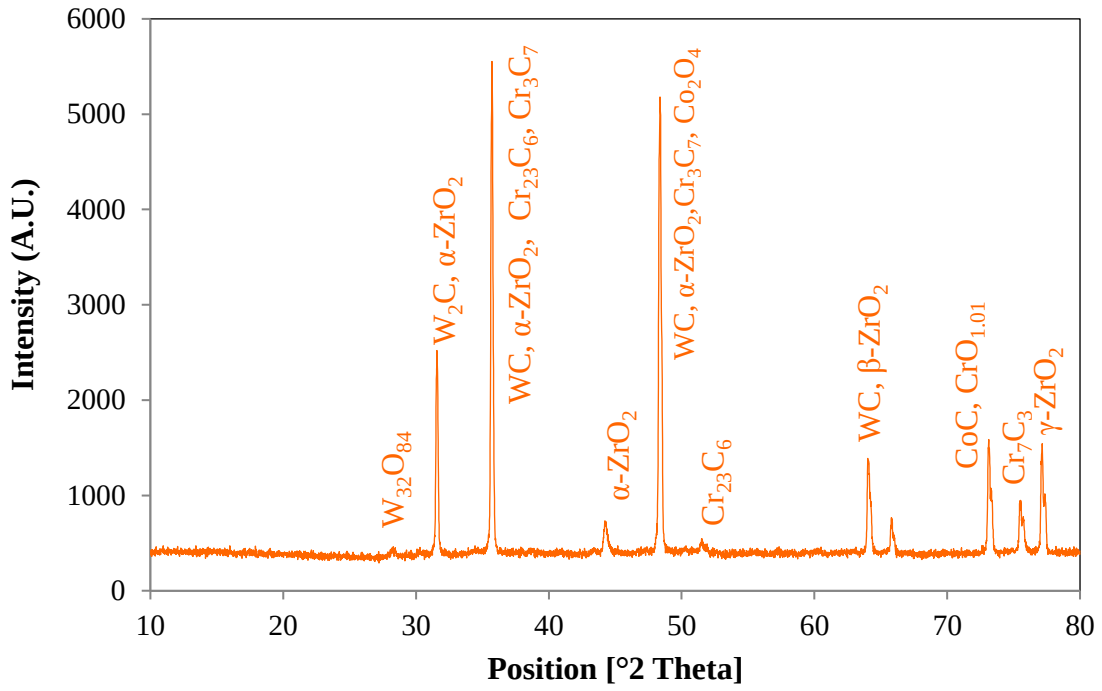


Figure 5.15. XRD spectrums of WC-10Co-4Cr+3%ZrO₂ coating.

5.4.3 Surface roughness analysis

The coated surfaces were also characterized in terms of average roughness which was measured with the help of roughness a Surftest Surface Roughness Tester (Model: SJ-400, manufactured by Mitutoyo; USA). In present study, terms Ra , Rq and Rz were evaluated by using the equations given by Leigh and Berndt (1994):

$$Ra = \frac{1}{L} \int_0^L |y - R_{peak}| dx \quad (5.1)$$

$$Rq = y_{\max} - y_{\min} \quad (5.2)$$

$$Rq = \frac{1}{n} \left[\sum_{i=0}^n Z_i \right] \quad (5.3)$$

During the roughness experiments, the test area thickness was kept constant, at 1.25 mm. The roughness criterions used in present study are shown in Figure 5.16.

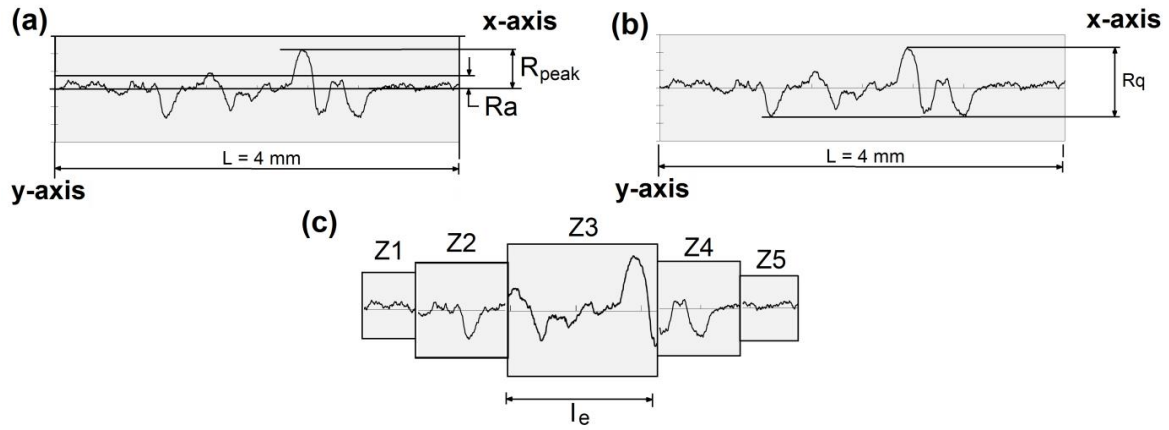


Figure 5.16. Roughness criterion (a) R_a (b) R_q , and (c) R_z .

The average surface roughness (R_a) value of WC-10Co-4Cr coating was found as $6.00 \mu\text{m}$, respectively. In the roughness plots, the values of R_q and R_z of the WC-10Co-4Cr coating were measured as 7.94 and $34.0 \mu\text{m}$, respectively (as shown in Figure 5.17). Also, the peaks of the roughness plots reveal that the peak-to-valley ratio was higher for the WC-10Co-4Cr coating than other coatings. This gives the WC-10Co-4Cr coating a greater average roughness. From Figure 5.18, the average roughness (R_a) of WC-10Co-4Cr+3% Y_2O_3 coatings was found as $4.47 \mu\text{m}$ whereas R_z and R_q were found as 17.2 and $5.07 \mu\text{m}$ respectively. Figure 5.19 represents the values of R_a and R_q were 3.74 and $4.64 \mu\text{m}$ respectively for WC-10Co-4Cr+3% Mo_2C coated surface. Figure 5.20 represents the values of R_a , R_q and R_z were 3.40 , 4.14 and $16.36 \mu\text{m}$ respectively for WC-10Co-4Cr+3% ZrO_2 coated surface. The order of roughness was found as:

- WC-10Co-4Cr > WC-10Co-4Cr+3% Y_2O_3 > WC-10Co-4Cr+3% Mo_2C > WC-10Co-4Cr+3% ZrO_2

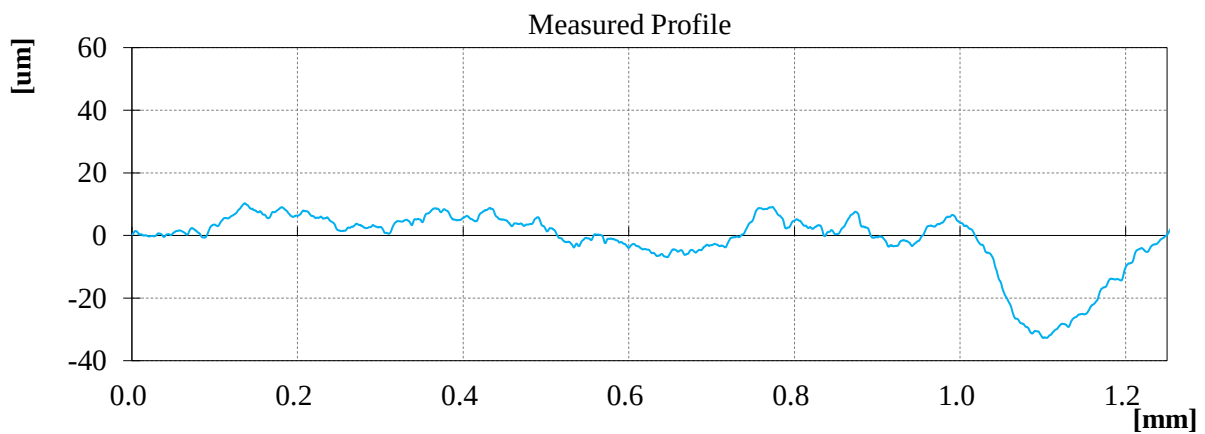


Figure 5.17. Roughness profile of WC-10Co-4Cr coatings.

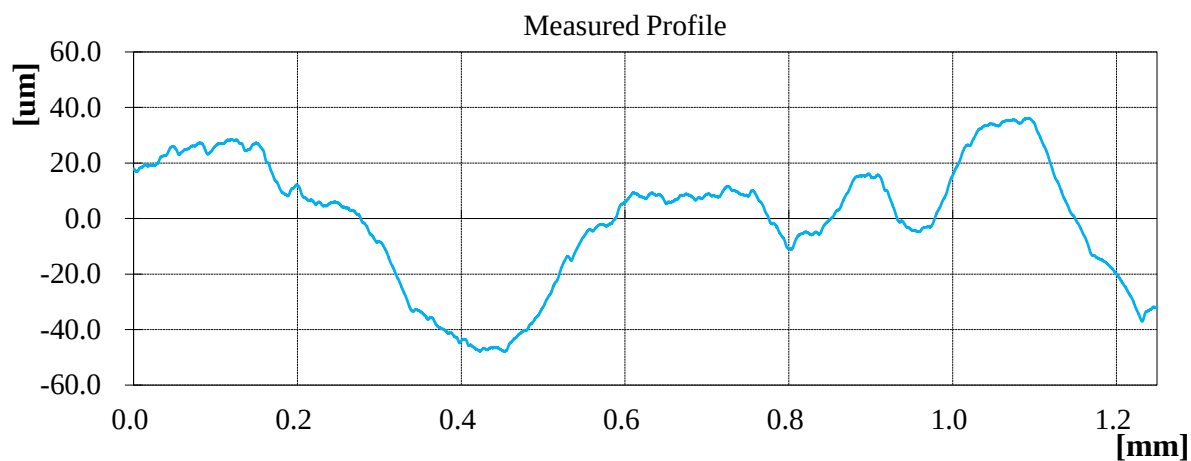


Figure 5.18. Roughness profile of WC-10Co-4Cr+3%Y₂O₃ coatings.

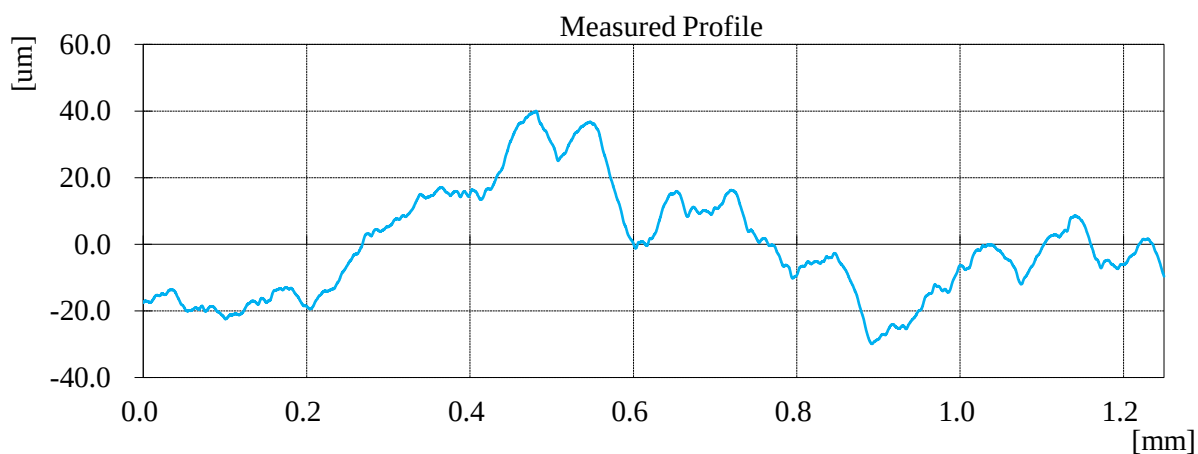


Figure 5.19. Roughness profile of WC-10Co-4Cr+3%Mo₂C coatings.

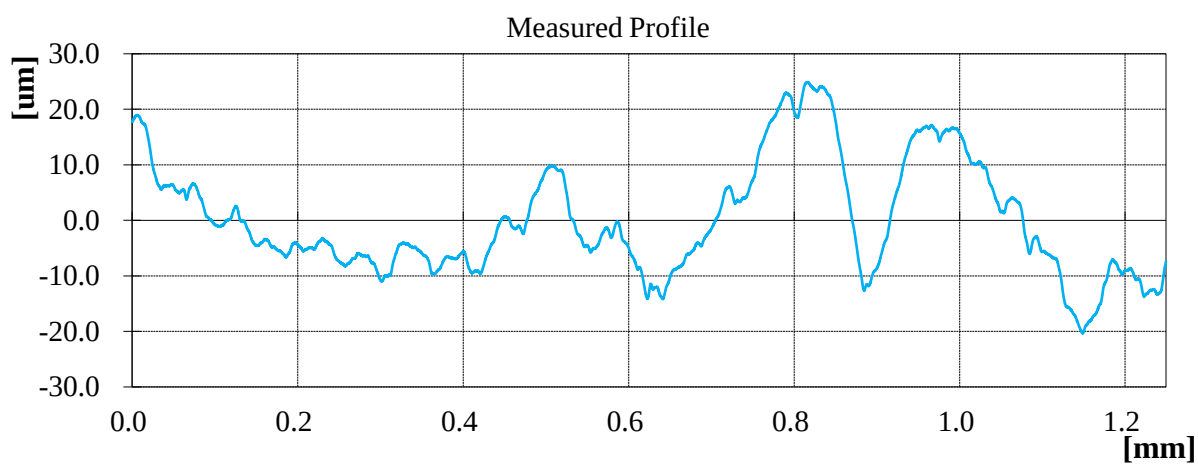


Figure 5.20. Roughness profile of WC-10Co-4Cr+3%ZrO₂ coatings.

5.4.4 Microhardness analysis

The microhardness of different cermet coatings was evaluated using the Vickers indentation method. A microhardness tester (Model: MVH-1, manufactured by Metatech; Pune, India) was used to measure the microhardness. During the testing, the indentation load varied from 500-1000 gms. The typical Vickers indentation marks on different coatings are shown in Figure 5.21. The average microhardness value of the WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings was found as 1156, 1164, 1123 and 1089 H.V. respectively. The microhardness values measured at the interfaces of the SS316L substrates coated with WC-10Co-4Cr coating was about 827.72 H.V. whereas 816.12, 802.09 and 786.33 H.V. respectively for WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C, and WC-10Co-4Cr+3%ZrO₂ coatings.

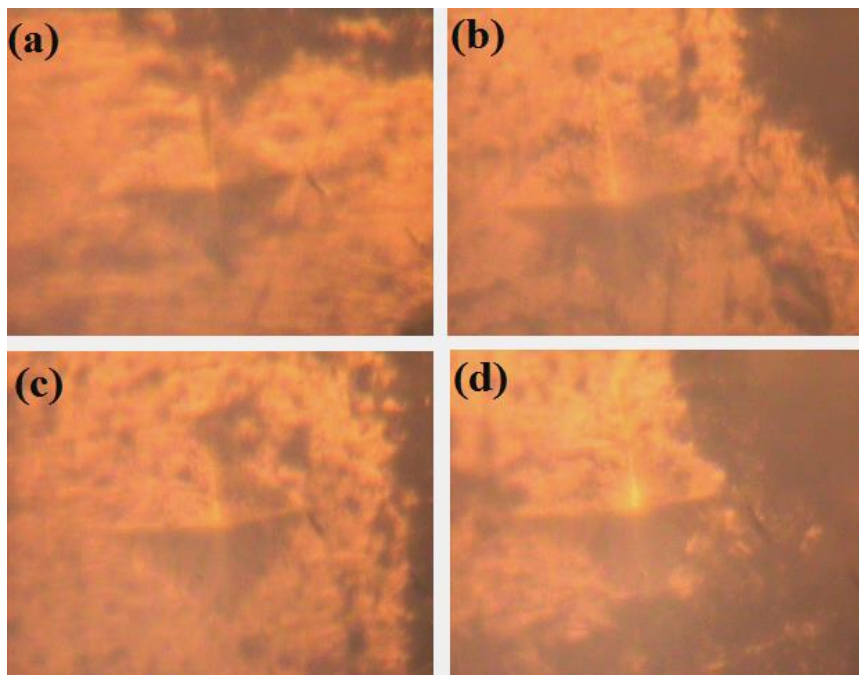


Figure 5.21. Vickers indentation marks on (a) WC-10Co-4Cr, (b) WC-10Co-4Cr+3%Y₂O₃, (c) WC-10Co-4Cr+3%Mo₂C, and (d) WC-10Co-4Cr+3%ZrO₂ coatings.

5.4.5 Mechanical properties

The fracture toughness of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C, and WC-10Co-4Cr+3%ZrO₂ coatings deposited surface was evaluated by using Vickers's indentation method. The indentation process was carried out by varying the load as 49.05, 98.1, 294.3 and 490.5 N. Generally, it is very tough to locate an indentation or Vickers's diagonal on a HVOF deposited surface using a typical optical microscope. Due to

this reason, the specimens were employed to JSM 6510LV scanning electron microscope for visualizing the precise image of Vickers's diagonals and cracks. The coating surface undergoes to cracks only while the load is applied along the thickness-axis along the cross-sectional area (i.e. along the interface). The indentation on interface resulted in generation of inter-lamellar cracks at coating-substrate interface. Measured values of Vickers's diagonals and crack lengths were put in the following correlation proposed by Niihara (1983) to estimate the fracture toughness:

$$K_C = 0.0711 \times (H_v \times \sqrt{d}) \times \left[\frac{E}{H_v} \right]^{\frac{2}{5}} \times \left[\frac{c}{d} \right]^{-\frac{3}{2}} \quad (5.4)$$

Vickers's microhardness is denoted by ' H_v ', elastic modulus is denoted by ' E '. The value of factor ' c ' was calculated by using the following equation:

$$c = \left(\frac{2d_{parallel} + 2d_{perpendicular}}{4} \right) \times \left(\frac{a_1 + a_2}{2} \right) \quad (5.5)$$

In above equation, parallel and perpendicular diagonal lengths of Vickers's indents are denoted by terms ' $d_{parallel}$ ' and ' $d_{perpendicular}$ '. In Figure 5.22, crack lengths are represented by terms ' a_1 ' and ' a_2 '. The c/d ratio was found as over 2.5. The fracture toughness (K_C) values of the WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C, and WC-10Co-4Cr+3%ZrO₂ coatings were 8.6±0.64, 20.13±0.09, 2.3±0.42 and 0.18±0.17 MPa.m^{1/2}, respectively.

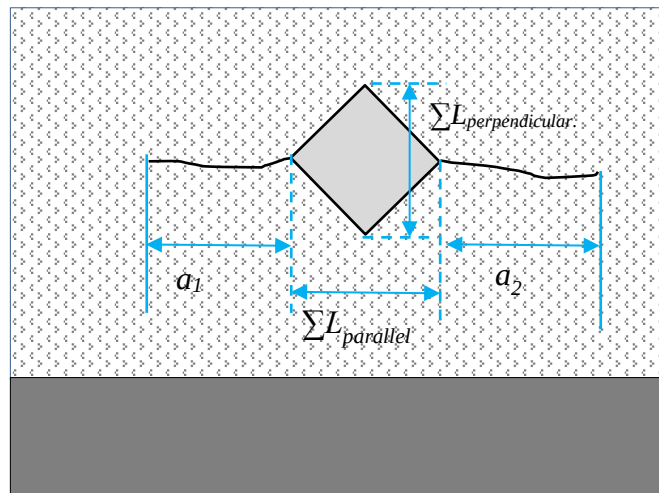


Figure 5.22. Schematic diagram of by Vickers's indentation.

5.5 EROSION WEAR ANALYSIS

5.5.1 Influence of velocity (V) on erosion wear of cermet coatings

In present study, the velocity of particles (V) was established by providing the rotational speed (N) to specimen. The velocity of bulk particles is directly proportional to the rotational speed of pot tester rotor in which sample is fixed. Therefore, the velocity of particles is represented by rotational speed of rotor at different levels. The rotational speed of specimen and velocity of particles follows the relationship written as:

$$V_{particles} \propto N_{specimen} \quad (5.6)$$

Erosion wear (E) is dependent on following factors reported by Elkholy (1983):

$$E = k \times (V)^m \times (C)^n \times (d)^q \quad (5.7)$$

Where velocity of moving sand particles is represented by symbol ' V ', solid concentration of sand slurry is represented by symbol ' C ' and particle weighted mean diameter by ' d '. The variables K , m , n , and q are the constants. In present study, erosion wear is the relative weight loss from the specimen and measured as weight loss (in gm) per unit area (in m^2). Present erosion wear results were obtained from four trails by masking the one side specimen.

The erosion wear of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ at different rotational speeds of propeller for sand particles (at $C_w=30\%$, $\alpha=0^\circ$ and $T=180$ min) is shown in Figure 5.23(a). From the Figure 5.23(a), it is observed that the erosion wear is strongly influenced with rotational speed. It is also observed that WC-10Co-4Cr+3%Y₂O₃ coating exhibits higher slurry erosion resistance as compared to WC-10Co-4Cr, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings. The order of erosion wear is found as: WC-10Co-4Cr+3%Y₂O₃<WC-10Co-4Cr+3%Mo₂C<WC-10Co-4Cr<WC-10Co-4Cr+3%ZrO₂.

Similarly, the erosion wear of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ at different rotational speeds of propeller for fly ash particles (at $C_w=30\%$, $\alpha=0^\circ$ and $T=180$ min) is shown in Figure 5.23(b). It was observed that the increment in erosion wear with increase in rotational speed was higher in case of fly

ash particles. However, the sand particles are coarser as compared to fly ash particles. The sand particles generated more erosion wear than fly ash particles. As the number of revolutions of rotor increases consequently the relative motion between sample specimen and slurry particles increases which tends toward action of high impact forces on specimen thus, high wear occurred (Gandhi et al. 1999; Gandhi et al. 2003; Desle et al. 2006). The general observation from graphical data reveals that the increment of erosion wear was non-linear during the experiments.

Figure 5.23(c) represents the erosion wear of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ at different rotational speeds of propeller for bottom ash particles (at $C_w=30\%$, $\alpha=0^\circ$ and $T=180$ min). The erosion wear generated by bottom ash particles was higher than the fly ash particles whereas lower than the sand particles.

In Equation 5.7, the value of velocity exponent (m) was found as 1.26, 1.99, and 1.79 respectively for sand, fly ash and bottom ash slurry. The value of ' m ' found to be in range (1.0-2.5) mentioned by researchers (Elkholy, 1983).

Present results deny the three possibilities of velocity exponent which are written as:

- Condition 1 ($m=1$) represents the direct proportionality of erosion wear with velocity of particles (i.e. rotational speed).
- Condition 2 ($m>1$) represents the non-linear proportion of erosion wear with velocity of particles.
- Condition 3 ($m=2$) represents the direct proportion of erosion wear with kinetic energy of particles striking to the surface. In this condition, particles rebound from the surface of specimen.

In present study, result follows the condition ' $1<m<2$ ' which shows the closure to the condition 1. So, it confirms the non-linear augmentation of erosion wear with velocity of particles (i.e. rotational speed). Furthermore, the increase in rotational speed of impeller shaft imposes a relative motion between specimen and sand slurry particles. This relative motion generates action of impact forces on specimen which results in erosion wear. Higher the rotational speed, more impact forces is that imposed high erosion wear (Elkholy, 1983; Gandhi et al. 2003).

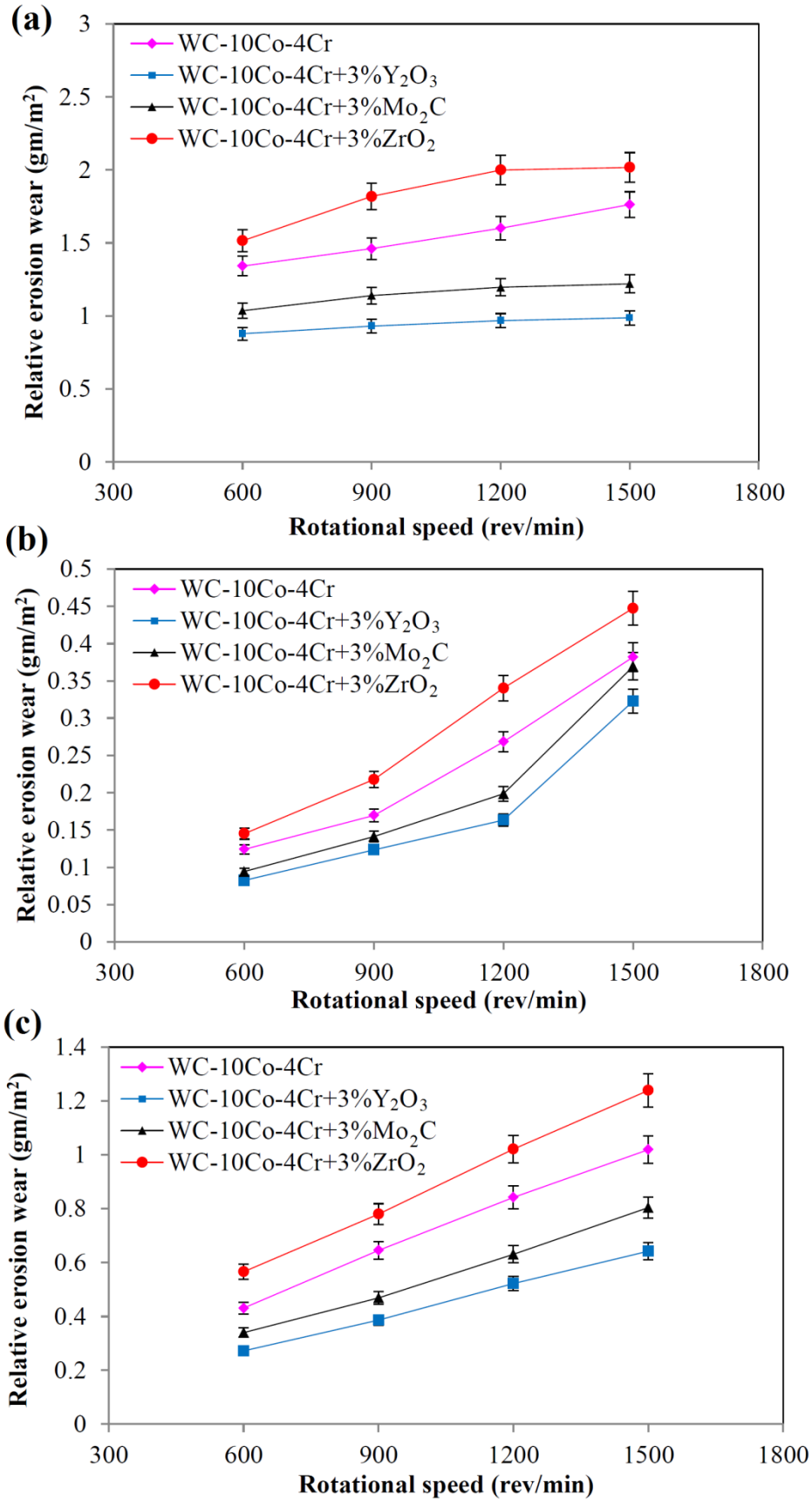


Figure 5.23. Effect of velocity on erosion wear due to (a) sand, (b) fly ash and (c) bottom ash slurries at $C_w = 30\%$ and $T = 180$ min.

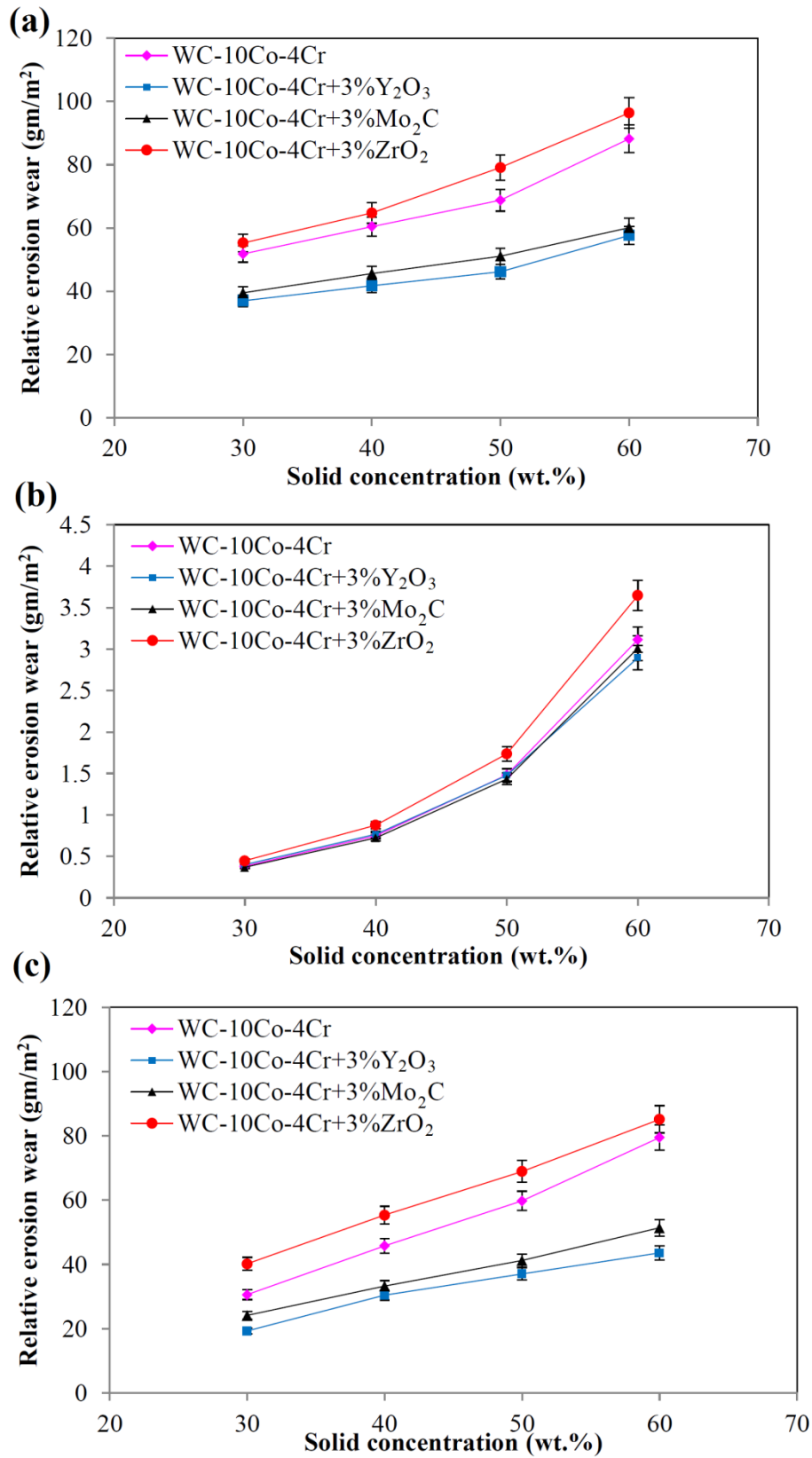


Figure 5.24. Effect of solid concentration on erosion wear due to (a) sand, (b) fly ash and (c) bottom ash slurries at $N = 1500$ rev/min and $T = 180$ min.

5.5.2 Influence of solid concentration (C_w) on erosion wear of cermet coatings

The erosion rate of erosion rate of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings at different solid concentrations of sand slurry ($N=1500$ rev/min, $\alpha=0^\circ$ and $T=180$ min) is shown in Figure 5.24(a). From Figure 5.24(a), it is found that erosion wear was increased non-linearly with increase in slurry concentration. Initially, the erosion rate increases at very faster rate for $C_w=30-40\%$, afterwards the increasing rate of erosion drops. The amount of bulk particles per unit volume increases due to increase in slurry concentration. Therefore, erosion rate is directly proportional to the amount of solid particles per unit volume. In other words, higher concentration allows large number of solid particles strikes on the surface of sample specimen which tends to increase the erosion rate of material. Similar observation is made by researchers (Gandhi et al. 2001; Desale et al. 2006). The mass of erodent particles decreases due to impact between specimen surface and erodent particle which was countered by using fresh slurry in each experimental run. Furthermore, the concentration of slurry remains unaffected with this process however, the diameter of erodent particles changes a bit after friable process. This happens because the mass loss from sample is a function of particle size. Larger particles exhibit high kinetic energy as compared to smaller particles and withstand comminution longer (Ojala et al. 2014).

Figure 5.24(b) represents the erosion wear of different cermet coatings by fly ash particles at different solid concentrations. From Figure 5.24(b), it can be observed that trend of erosion wear by fly ash was different from erosion wear by sand slurry. Erosion wear due to fly ash shows steeper increase in magnitude with increase in solid concentration. Fly ash particles have low void fraction as compared to sand particles due to the reason the increase in solid concentration of fly ash results in large number of particles in a given volume. Thus, the increment in erosion wear was high as compared to sand slurry. Figure 5.24(c) represents the erosion wear of different cermet coatings by bottom ash particles at different solid concentrations. It was observed that the increment in erosion wear was almost same for each 10% increase in solid concentration of fly ash.

- ❖ The order of erosion wear is found as: WC-10Co-4Cr+3%Y₂O₃<WC-10Co-4Cr+3%Mo₂C<WC-10Co-4Cr<WC-10Co-4Cr+3%ZrO₂.

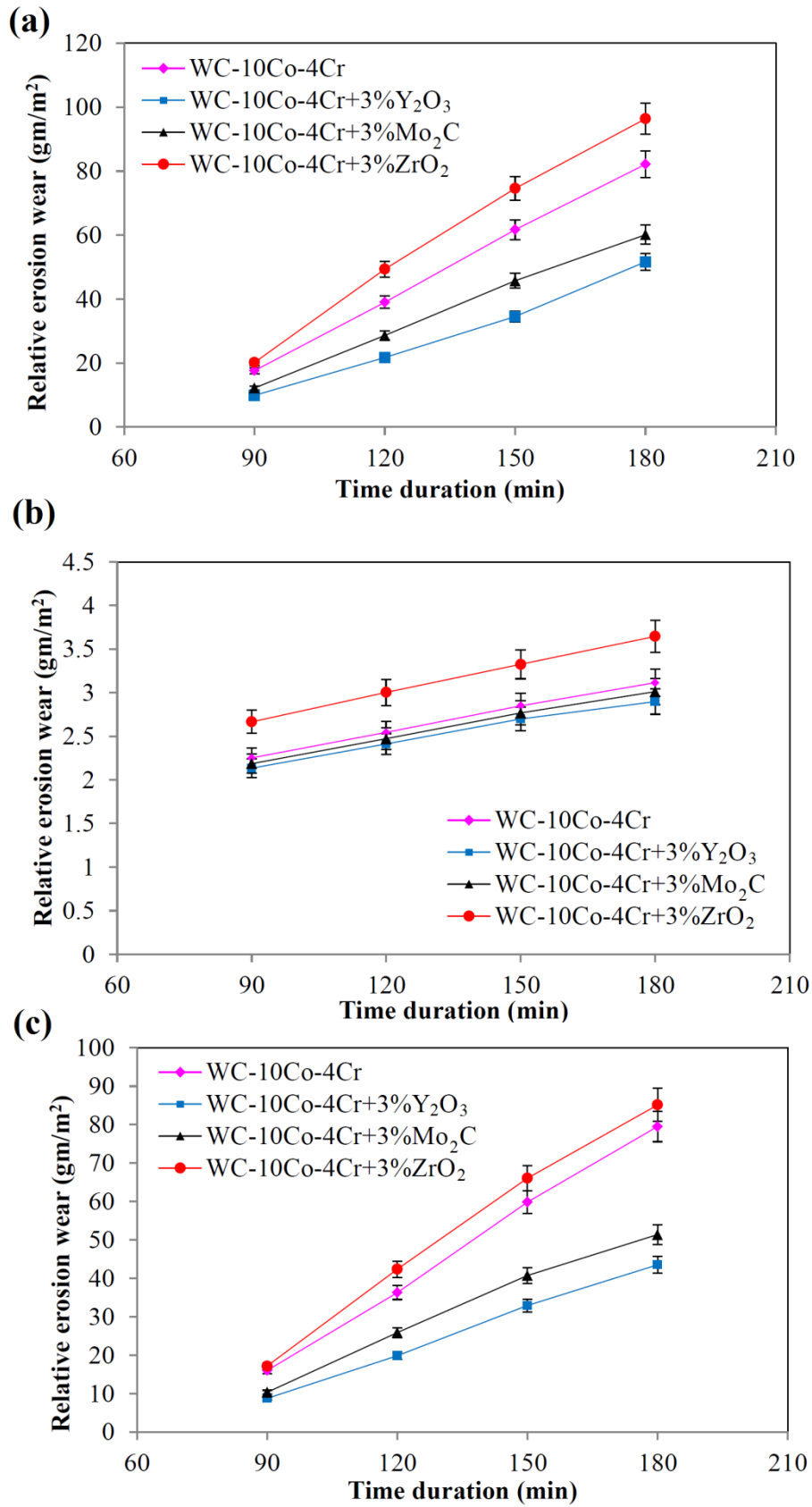


Figure 5.25. Effect of time duration on erosion wear due to (a) sand, (b) fly ash and (c) bottom ash slurries.

5.5.3 Influence of time duration (T) on Erosion wear of cermet coatings

Effect of time duration on the erosion wear of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings by sand slurry is shown in Figure 5.25(a). The erosion wear experiments were performed at four different time durations namely 90, 120, 150 and 180 minutes at $N=1500$ rev/min, $\alpha=0^\circ$ and $C_w=60\%$. The erosion wear of different specimens was increased with time variation. The minimum erosion wear is encountered at 90 minutes with WC-10Co-4Cr+3%Y₂O₃. The rate of increase in erosion rate with time duration was found approximately linear.

The results of the relative erosion wear by fly ash slurry established by different time durations are represented in Figure 5.25(b). From Figure 5.25(b), it can be seen that erosion wear failure increases with increases in time duration. Erosion wear was found to be more linear for fly ash particles. This may be due to the fact that the fly ash particles exhibit spherical shape. The shape of fly ash particles doesn't change much with time durations. It remains spherical even after erosion wear phenomenon. However, the bottom ash particles show the steeper increase in erosion wear with increase in time durations (as shown in Figure 5.25(c)).

5.5.4 Influence of impact angle (α) on Erosion wear of cermet coatings

Ducom TR-41 pot tester is used in present study has its own limitation i.e. workpiece can be placed at horizontal position which indicates the erosion wear at low impact angle (0°). To overcome from this limitation, different impact angle arrangements were manufactured, as shown in Figure 5.26. These arrangements were manufactured by using square face rod having dimensions $1/2 \times 1/2$ inch (i.e. length $\times$ width). The threads on these impact angle arrangements were cut by using GNM-22 conventional lathe (manufactured by New Bharat Engineering Works Ltd., Jamnagar, India), shown in Figure 5.27.

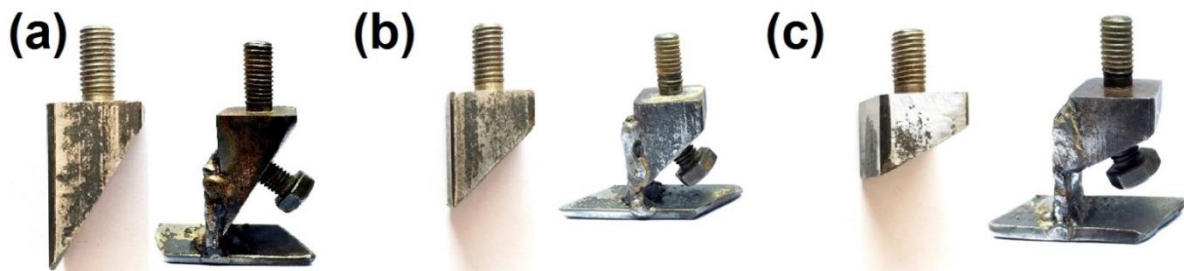


Figure 5.26. Impact angle arrangements.



Figure 5.27. GNM-22 conventional lathe

Figure 5.28(a) shows the erosion wear results at different impact angles between sand particles and specimen. It was found that the maximum erosion was observed at impact angle of 60° arrangement for all cermet coatings. The trend of erosion wear indicates that of WC-10Co-4Cr+3%Mo₂C coatings shows the brittle behavior, of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings shows the brittle as well as ductile behavior. The order of erosion wear for sand slurry is found as:

- WC-10Co-4Cr+3%Y₂O₃ < WC-10Co-4Cr+3%Mo₂C < WC-10Co-4Cr+3%ZrO₂ < WC-10Co-4Cr (at $\alpha = 0^\circ$).
- WC-10Co-4Cr+3%Mo₂C < WC-10Co-4Cr+3%Y₂O₃ < WC-10Co-4Cr < WC-10Co-4Cr+3%ZrO₂ (at $\alpha = 30^\circ$).
- WC-10Co-4Cr+3%Mo₂C < WC-10Co-4Cr+3%Y₂O₃ < WC-10Co-4Cr < WC-10Co-4Cr+3%ZrO₂ (at $\alpha = 45$ and 60°).

The erosion wear of cermet coatings at different impact angles between fly ash particles and specimen is shown in Figure 5.28(b). Similar observations were made for fly and bottom ash slurry. The order of erosion wear is found as:

- WC-10Co-4Cr+3%Mo₂C < WC-10Co-4Cr+3%Y₂O₃ < WC-10Co-4Cr < WC-10Co-4Cr+3%ZrO₂ (at $\alpha = 0, 30, 45$ and 60°).

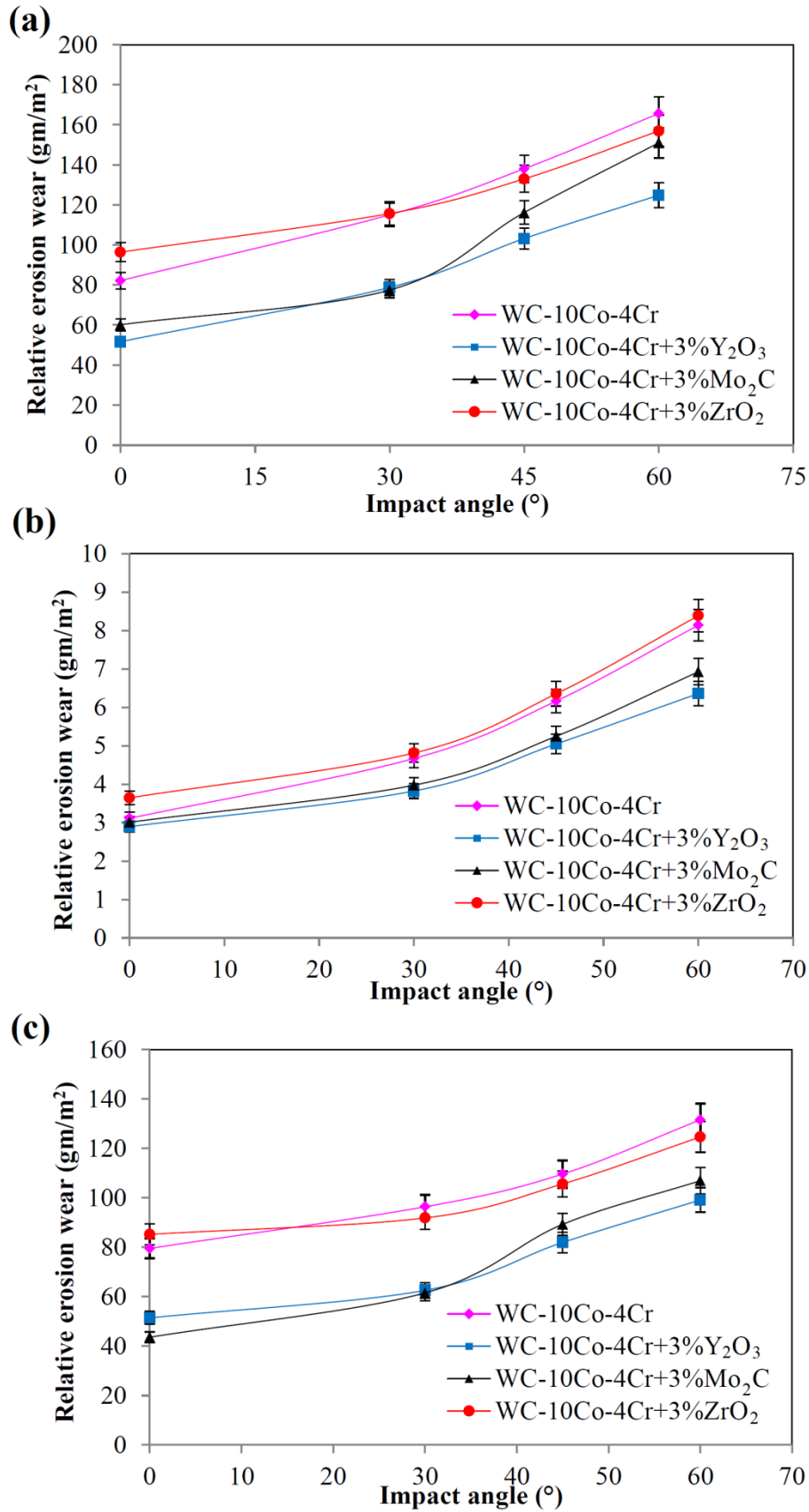


Figure 5.28. Effect of impact angle on erosion wear due to (a) sand, (b) fly ash and (c) bottom ash slurries at $C_w = 60\%$ and $N = 1500$ rev/min.

The maximum erosion was observed at impact angle of 60° arrangement for all cermet coatings. Figure 5.28(c) shows the erosion wear results at different impact angles between bottom ash particles and specimen. The order of erosion wear is found as:

- WC-10Co-4Cr+3%Mo₂C < WC-10Co-4Cr+3%Y₂O₃ < WC-10Co-4Cr < WC-10Co-4Cr+3%ZrO₂ (at $\alpha = 0^\circ$).
- WC-10Co-4Cr+3%Mo₂C < WC-10Co-4Cr+3%Y₂O₃ < WC-10Co-4Cr+3%ZrO₂ < WC-10Co-4Cr (at $\alpha = 30^\circ$).
- WC-10Co-4Cr+3%Y₂O₃ < WC-10Co-4Cr+3%Mo₂C < WC-10Co-4Cr+3%ZrO₂ < WC-10Co-4Cr (at $\alpha = 45$ and 60°).

5.6 MICROSTRUCTURE OF ERODED COATINGS

The erosion wear mechanisms of different coatings deposited on SS316L are also studied in present work. SEM of eroded surface was carried out to analyze the surface morphology of all specimens. The material properties directly contribute in erosion wear which largely depends upon the mechanism of material removal. The investigators recommended that cutting, fracture and abrasion are the major mode of erosion wear mechanism that is relevant to centrifugal slurry pump (Gandhi et al. 1999; Gandhi et al. 2003). The eroded surface SEM micrographs of WC–10Co–4Cr coating for sand slurry are shown in Figure 5.29(a). From Figure 5.29(a), the major proportion of tungsten carbide phase can be visualized on the surface of WC-10Co-4Cr coating. Eroder particles were also observed on the eroded surfaces due to embedment of hard eroder particles in the relative soft matrix to cobalt which can be found in SEM images. The presence of wear marks can be observed on worn surface caused by micro cutting/ploughing, carbide-fracture and lip formation. It is also found that surface wear by the micro-crater is responsible for material removal. Figure 5.29(b) reveals the brittle fractures and microcutting on the surface of WC-10Co-4Cr+3%Y₂O₃ coatings. Smeared region was observed throughout the surface of WC-10Co-4Cr+3%Mo₂C coating, as shown in Figure 5.29(c). WC-10Co-4Cr+3%ZrO₂ shows the deep craters at many regions in a small area of coating. Zr-phase undergoes to the microcutting action which can be visualized in Figure 5.29(d).

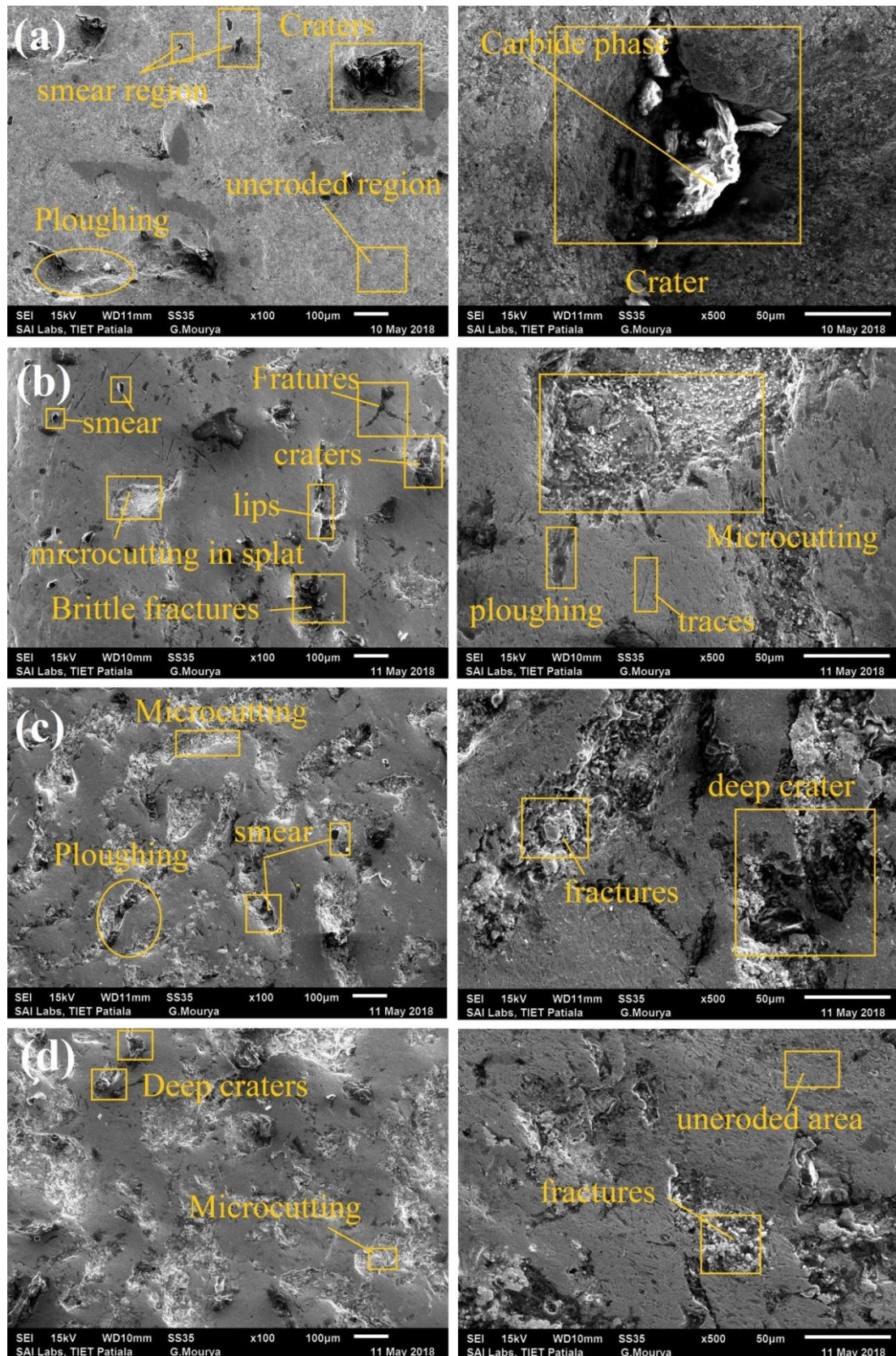


Figure 5.29. Erosion wear mechanism by sand slurry on the surface of (a) WC-10Co-4Cr, (b) WC-10Co-4Cr+3%Y₂O₃, (c) WC-10Co-4Cr+3%Mo₂C and (d) WC-10Co-4Cr+3%ZrO₂.

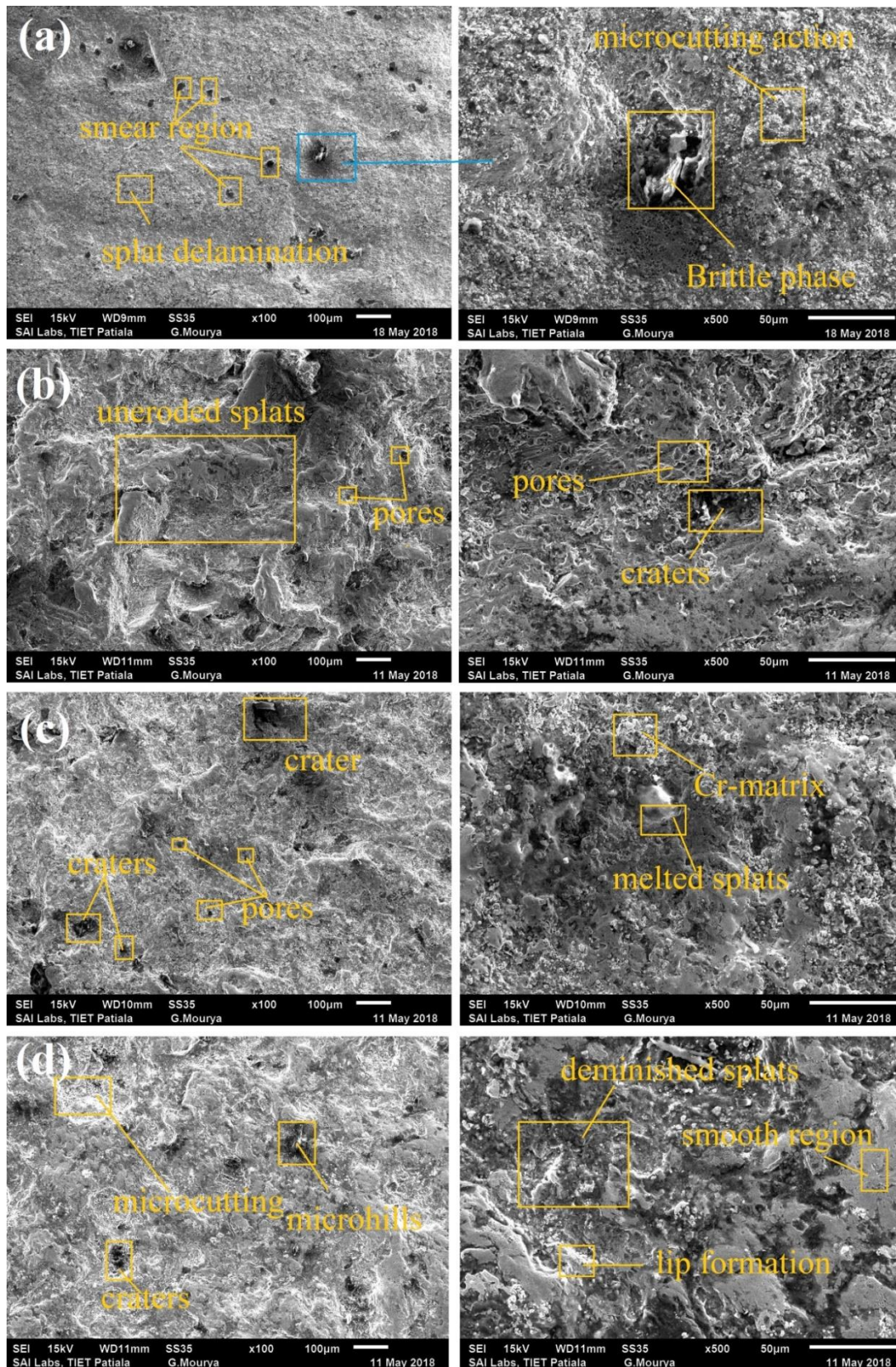


Figure 5.30. Erosion wear mechanism by fly ash slurry on the surface of (a) WC-10Co-4Cr, (b) WC-10Co-4Cr+3%Y₂O₃, (c) WC-10Co-4Cr+3%Mo₂C and (d) WC-10Co-4Cr+3%ZrO₂.

The erosion wear mechanisms by fly ash slurry on the surface of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings is shown in Figure 5.30. From Figure 5.30(a), the presence of wear marks can be observed on worn surface caused by microcutting/ploughing, carbide-fracture and lip formation. It is also found that surface wear by the micro-crater is responsible for material removal. From these figures, it can be clearly observed that fly ash causes more microcutting action as compared to sand particles. It was also observed that the microhills were present in WC-10Co-4Cr coating.

Figure 5.30(b) represents the erosion wear mechanisms generated by the fly ash particles on the surface of WC-10Co-4Cr+3%Y₂O₃ coating. The erosion wear occurs on the surface of WC-10Co-4Cr+3%Y₂O₃ coating was comparatively lower than WC-10Co-4Cr coating. During the erosion wear process the splats remains undiminished. Few pores were seen in SEM micrographs.

Figure 5.30(c) represents the eroded surface of WC-10Co-4Cr+3%Mo₂C coatings with fly ash. The craters and pores were seen throughout the surface of WC-10Co-4Cr+3%Mo₂C coating. The microcutting and plastic deformations were obviously appeared on the eroded surface. Melted splats also appeared at few regions. The grayish portion in SEM micrograph represents the Cr-matrix which underwent to microcutting action. The erosion wear mechanism on the surface of WC-10Co-4Cr+3%ZrO₂ coating by fly ash particles is shown in Figure 5.30(d). Deep craters and ploughing marks were observed on the surface of WC-10Co-4Cr+3%Mo₂C coatings. The microcutting, lip formation and diminished splats were appeared on the eroded surface. The Cr-microhills were also appeared on the surface of WC-10Co-4Cr+3%ZrO₂ coating.

The erosion wear mechanisms by bottom ash slurry on the surface of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings is shown in Figure 5.30. Deep craters were observed on the surface of WC-10Co-4Cr coating, as shown in Figure 5.31(a). Lip formation was observed at the edges of splats. However, the splats seem to be diminished at most of the regions. The diminished splats also underwent to the microcutting action. From Figure 5.31(b), few splats were observed on the surface of WC-10Co-4Cr+3%Y₂O₃ coating. Commonly observed mechanisms were smear regions, ploughing and craters. Yttria phase was also observed as light grey region in WC-10Co-4Cr+3%Y₂O₃ coating. The WC-10Co-4Cr+3%Mo₂C coating shows the carters, ploughing and cutting action on the eroded surface, as seen from Figure 5.31(c). Few microhills were observed in the SEM micrographs. The particle tracks were also appeared on the diminished surfaces of splats. The WC-10Co-4Cr+3%ZrO₂ coating show splat delamination, deep craters

and ploughing (as represented in Figure 5.31(d)). Zr-doped regions show flooded regions which could be limitation of WC-10Co-4Cr+3%ZrO₂ coating. ZrO₂ addition in WC-10Co-4Cr could be beneficial in corrosion problems.

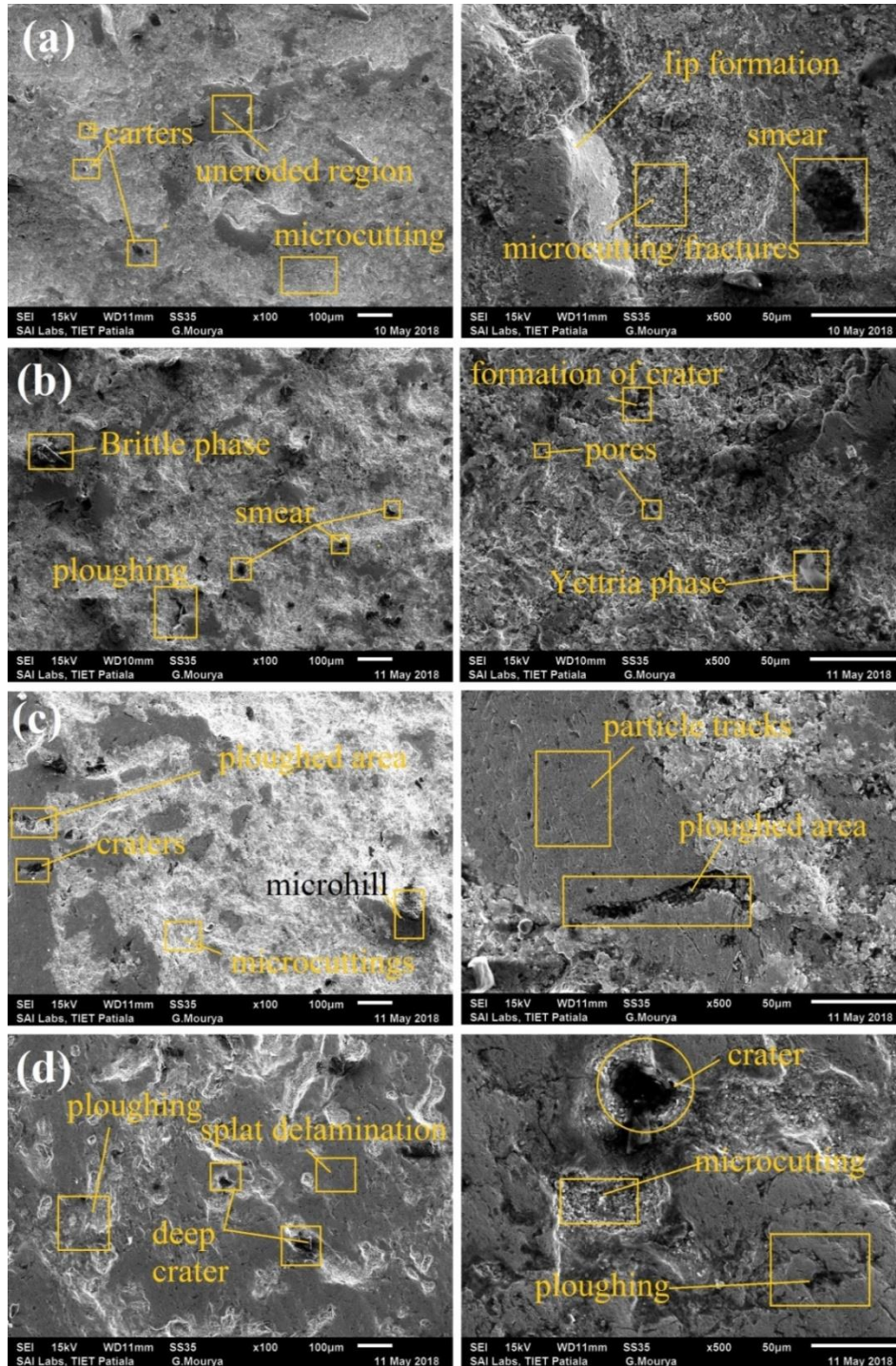
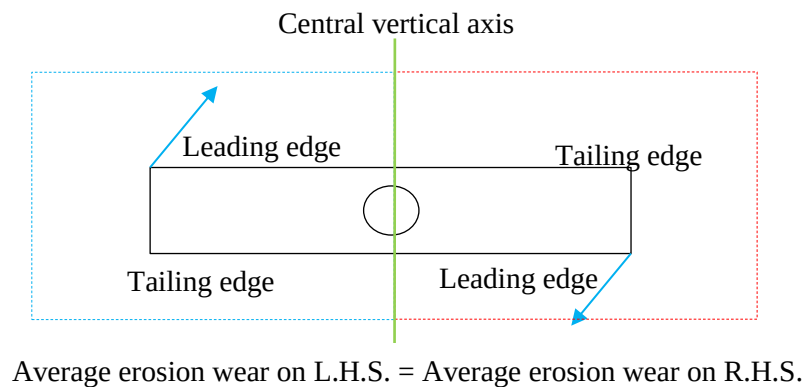


Figure 5.31. Erosion wear mechanism by bottom ash slurry on the surface of (a) WC-10Co-4Cr, (b) WC-10Co-4Cr+3%Y₂O₃, (c) WC-10Co-4Cr+3%Mo₂C and (d) WC-10Co-4Cr+3%ZrO₂.

5.7 REMARKS

- The fracture toughness (K_{IC}) values of the WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C, and WC-10Co-4Cr+3%ZrO₂ coatings were 8.6±0.64, 20.13±0.09, 2.3±0.42 and 0.18±0.17 MPa.m^{1/2}, respectively.
- The order of roughness for WC-Co-Cr coatings was found as:
WC-10Co-4Cr > WC-10Co-4Cr+3%Y₂O₃ > WC-10Co-4Cr+3%Mo₂C > WC-10Co-4Cr+3%ZrO₂
- The average microhardness value of the WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings was found as 1156, 1164, 1123 and 1089 H.V. respectively.
- The order of erosion wear with change in solid concentration, velocity and time duration is found as: WC-10Co-4Cr+3%Y₂O₃<WC-10Co-4Cr+3%Mo₂C<WC-10Co-4Cr<WC-10Co-4Cr+3%ZrO₂.
- The order of erosion wear for different erodents was found as: sand > bottom ash > fly ash.
- The trend of erosion wear indicates that of WC-10Co-4Cr+3%Mo₂C coatings shows the brittle behavior, of WC-10Co-4Cr, WC-10Co-4Cr+3%Y₂O₃, WC-10Co-4Cr+3%Mo₂C and WC-10Co-4Cr+3%ZrO₂ coatings shows the brittle as well as ductile behavior.



Sample rotating in clockwise direction

Figure 5.32. Phenomenon of erosion wear at leading and trailing surface.

5.8 CLOSURES

For every experiment, the erosion wear occurs in different pattern on the surface. However, distance between the center of rotation and transverse edges is very small. So, the velocity experienced by the both samples at different locations from the center of rotation would marginally changes. The erosion wear occurred at leading surface was found high as compared to tailing surface and its effect was accounted by taking average weight loss from the surface of the sample. Moreover, the sample specimen undergo to equal average erosion wear from central vertical axis to the both sides of specimen, as shown in Figure 5.31.

CHAPTER 6

EROSION WEAR OF METAL COMPOSITE COATINGS: PART III

EROSION WEAR OF METAL COMPOSITE COATINGS: PART III

In this chapter, the erosion wear of different metal composite coatings was analyzed. SS316L was taken as the substrate material. This chapter also covers the pre-experimental analyses like surface microstructure, chemical composition, coating thickness, crystalline structures and various mechanical properties of coatings.

6.1 DETAILS OF COATING POWDERS

Thermal spraying powders namely Cr_2O_3 , Stellite-6 and Colmonoy-88 were purchased from M/S Metalizing Equipment Company Pvt. Ltd. Jodhpur (India). Nickel (Ni) powder was purchased from LOBA Chemie Pvt. Ltd. Mumbai (India). Aluminum (Al) metal and TiO_2 composite powders were purchased from high purity laboratory chemicals (HPLC) Pvt. Ltd. Sriram, (India). Al_2O_3 was purchased from Pioneer In-organics, Delhi (India). Figure 6.1 shows the surface morphology and chemical composition of these thermal spraying powders. Morphological analysis of Stellite-6 and Colmonoy-88 also revealed that these powders were uniformly fused and having a pure spherical shape. Cr_2O_3 powder had elliptical rode-like shaped particles. Nickel (Ni) and Al_2O_3 powder particles were found irregular and blocky in shape. The details of thermal spraying powders are mentioned in Table 6.1. Blending was performed to make different combinations of coating powders.

Table 6.1: Details of thermal spraying powders

Powders	Grade	Particle size	Base of powder
Stellite	6	45±15 µm	Co
Colmonoy	88	45±15 µm	Ni
Nickel	Pure 99.99%	45±15 µm	Ni
Aluminum	Pure 99.99%	60±15 µm	Al
Cr_2O_3	Pure	30±15 µm	Cr
Al_2O_3	Pure	60±15 µm	Al
TiO_2	Industrial (+1% SiO_2)	1-15 µm	Ti

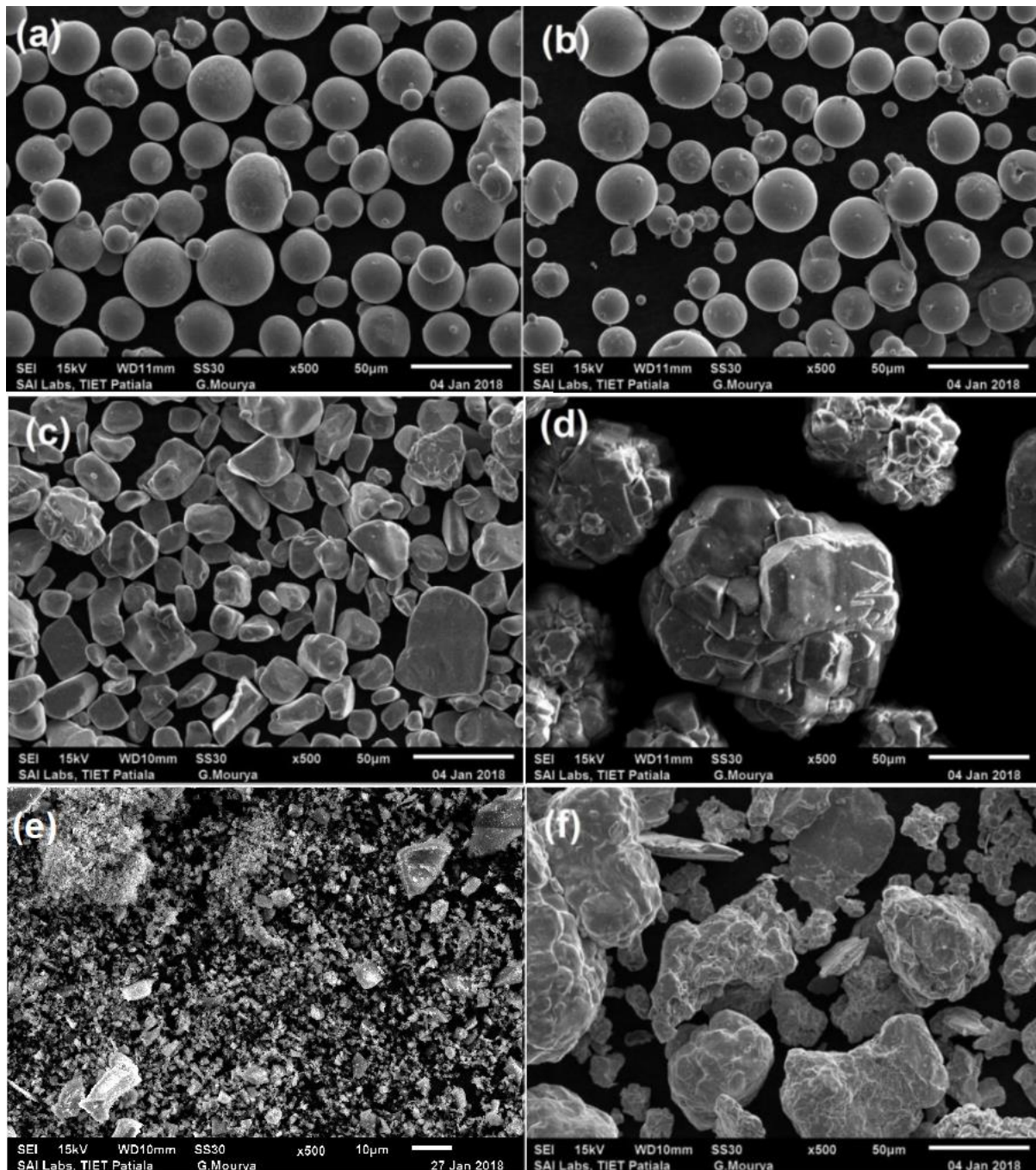


Figure 6.1. Surface morphology of (a) Stellite-6, (b) Colmonoy-88, (c) Cr_2O_3 , (d) Al_2O_3 , (e) TiO_2 and (f) Nickel spraying powders at magnification of 500x.

6.2 HVOF SPRAYING PROCESS

High-velocity oxy-fuel (HVOF) spraying was performed at Harsha Specialty Welding and Coatings, Panchkula, India using a HVOF MP-2100 unit and HP-2700 torch, as mentioned in previous chapter. The values of spraying parameters during HVOF process are mentioned in Table 6.3. Different combinations were prepared in order to optimize the combination of

powders. Ni-Cr₂O₃, Ni-Al₂O₃, and Al-TiO₂ powder was prepared in different combinations such as 90/10, 80/20 and 70/30 (in wt. %). The erosion wear experiments were performed at maximum rotation speed i.e. 1500 rev/min, solid concentration of 30% for the time duration of 180 minutes. The erosion wear results of different coating powders with different combinations are represented in Figure 6.2. It was found that the erosion wear was found minimum with for 80/20 ratio for Ni-Cr₂O₃, Ni-Al₂O₃, and Al-TiO₂ coating powders.

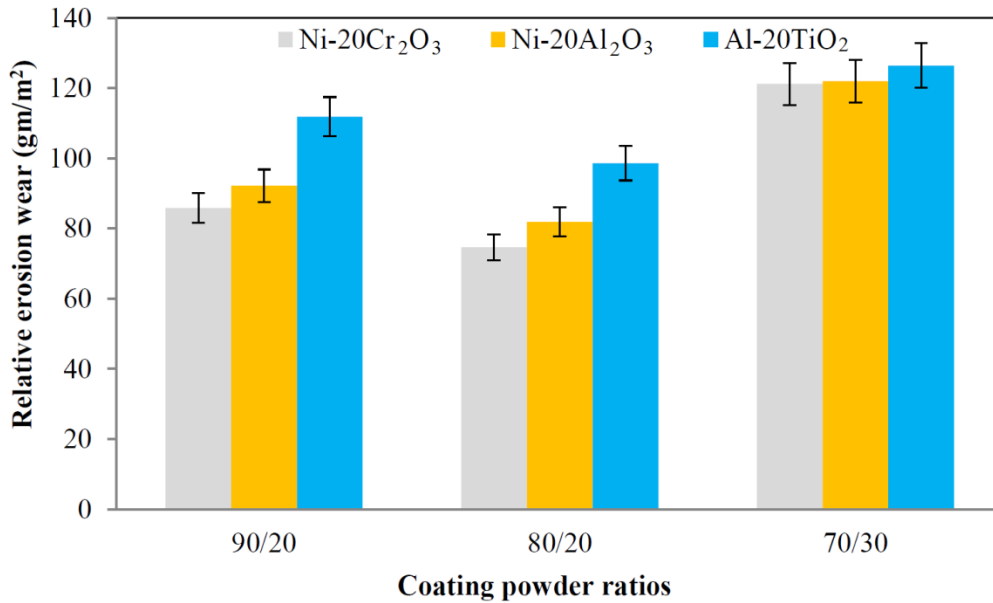


Figure 6.2. Erosion wear results of different coating powders with different combination.

Table 6.2: Spraying parameters during HVOF process

Spray parameter	Stellite-6/Colmonoy-	Ni-20Cr ₂ O ₃ /Ni-Al ₂ O ₃ /Al-
	88	20TiO ₂
Air flow rate (SPLM)	640	690
Air Pressure (kg/cm ³)	6	6
Oxygen flow rate (SLPM)	260	245
Oxygen Pressure (kg/cm ³)	10	10
LPG Fuel flow rate (SLPM)	60	70
Fuel Pressure (kg/cm ²)	7.5	7.5
Powder feed rate (g/min)	30	25
Spray distance (mm)	150	150

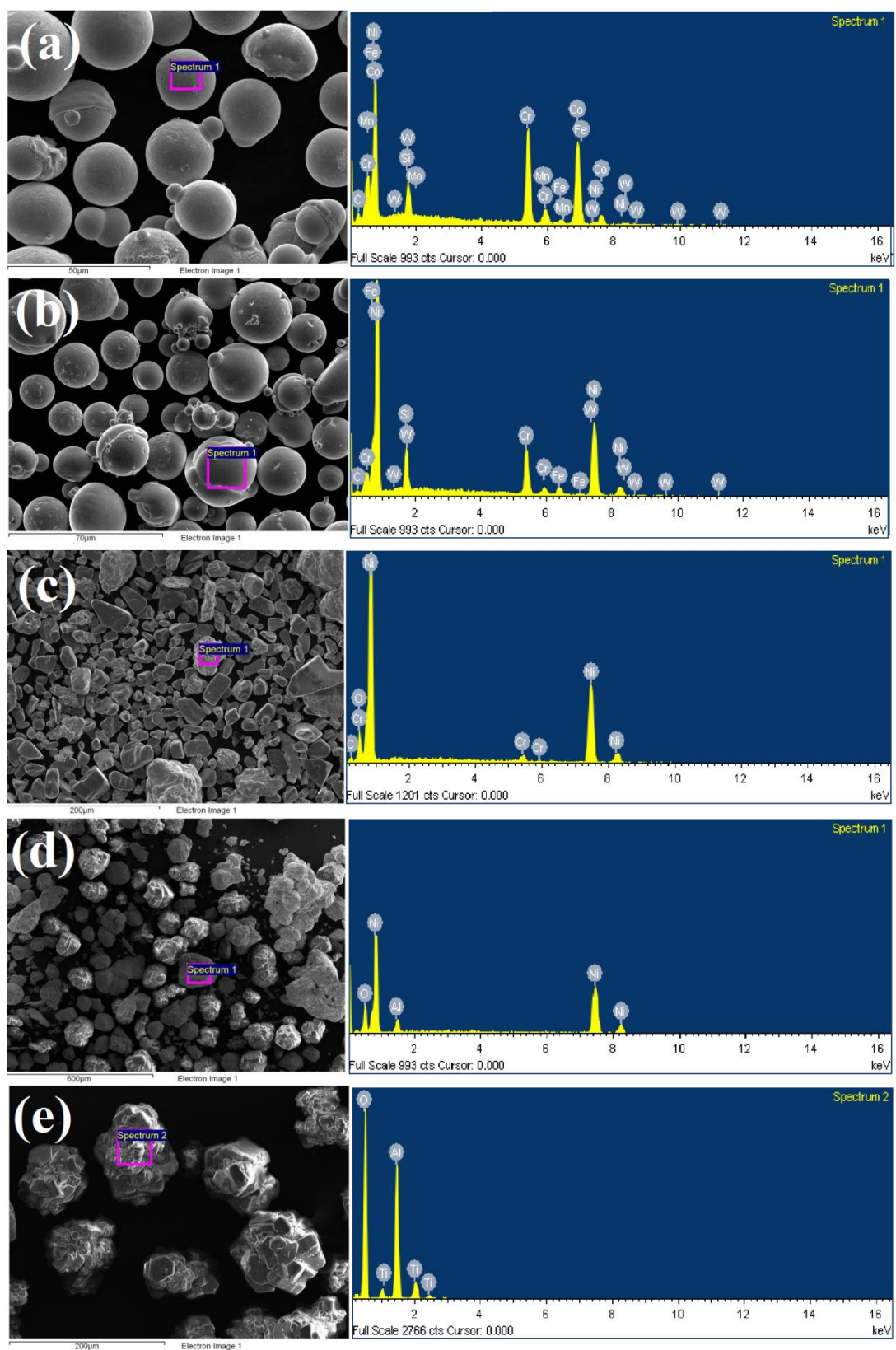


Figure 6.3. EDS spectrum of (a) Stellite-6, (b) Colmonoy-88, (c) Ni-20Cr₂O₃, (d) Ni-20Al₂O₃, and (e) Al-20TiO₂ coating powders.

6.3 PRE-EXPERIMENTAL ANALYSIS

6.3.1 *Compositional analysis of coating powders*

Energy dispersive spectroscopy as used to obtain the composition of various elements presents in different coating powders. The composition of Ni-20Cr₂O₃, Ni-Al₂O₃ and Al-TiO₂ were blended in a known composition whereas Stellite-6 and Colmonoy-88 coating powders are composed of different elements. The EDS spectrums of different coating powders namely Stellite-6, Colmonoy-88, Ni-20Cr₂O₃, and Ni-Al₂O₃ surface. The EDS spectrum confirms presence of W, Si, C, Cr, Mo, Mn, Ni, Fe and Co in percentage of 4.30, 1.33, 1.16, 30.80, 0.10, 0.30, 2.59, 2.25 and 57.17% respectively in Stellite-6, as shown in Figure 6.3(a). The EDS spectrum of Colmonoy-88 powder indicates the presence of W, Si, C, Cr, B, Fe and Ni in percentage of 17.37, 3.91, 0.84, 14.80, 3.18, 3.95 and 55.95% respectively in Stellite-6, as shown in Figure 6.3(b). The EDS spectrums of Ni-20Cr₂O₃, Ni-Al₂O₃ and Al-TiO₂ are shown in Figure 6.3(c-e).

6.3.2 *Surface morphology of as-sprayed surface*

Surface morphology of HVOF deposited surface was inspected through SEM micrographs. Figure 6.4 shows the SEM micrographs of different HVOF deposited. From SEM micrographs, the appearances of inter-lamellae splats can be visualized on HVOF deposited surfaces. The presence of lamellae microstructure represents an anisotropic nature of coated surface. Figure 6.4(a), rough lamellae splats and few un-burnt loosely bonded particles were appeared on the Stellite-6 deposited surface. Figure 6.4(b) indicates the splatted as well as smooth surface of Colomonoy-88 surface. Presence of splats was higher in case of Colmonoy-88 deposited surface. Figure 6.4(c) represents the surface morphology of Ni-20Cr₂O₃ coating. Few pores were visualized in between the splat section of Ni-20Cr₂O₃ coating. The Ni-20Al₂O₃ was found to be smoother as compared to Ni-20Cr₂O₃ coating. The formation of splats was competitively lower than other coatings, as shown in Figure 6.4(d). Al-20TiO₂ as-sprayed surface also shows the presence of lamellae splats.

Formation of splats during coating deposition is a rapid process. The adherence of splats with substrate depends upon the surface roughness of substrate. The dilution of splats i.e. remelting process ensures the bonding between different splats. The dilution of substrate layer and splats plays a phenomenal role during HVOF spraying process. During HVOF process, droplets of molten metal strike to substrate at very high velocity which results in

dilution of substrate layer and older splats nearby the interface region (Li et al. 2015; Yao et al. 2016). This represents the high bonding strength of coating with substrate at interface. The schematic diagram representing development of inter-lamellar splats in coating layers is shown in Figure 6.5. The formation of inter-lamellar splats at coating surface was obvious due interaction with surrounding environment which prevents the dilution process and provide rapid cooling to substrate.

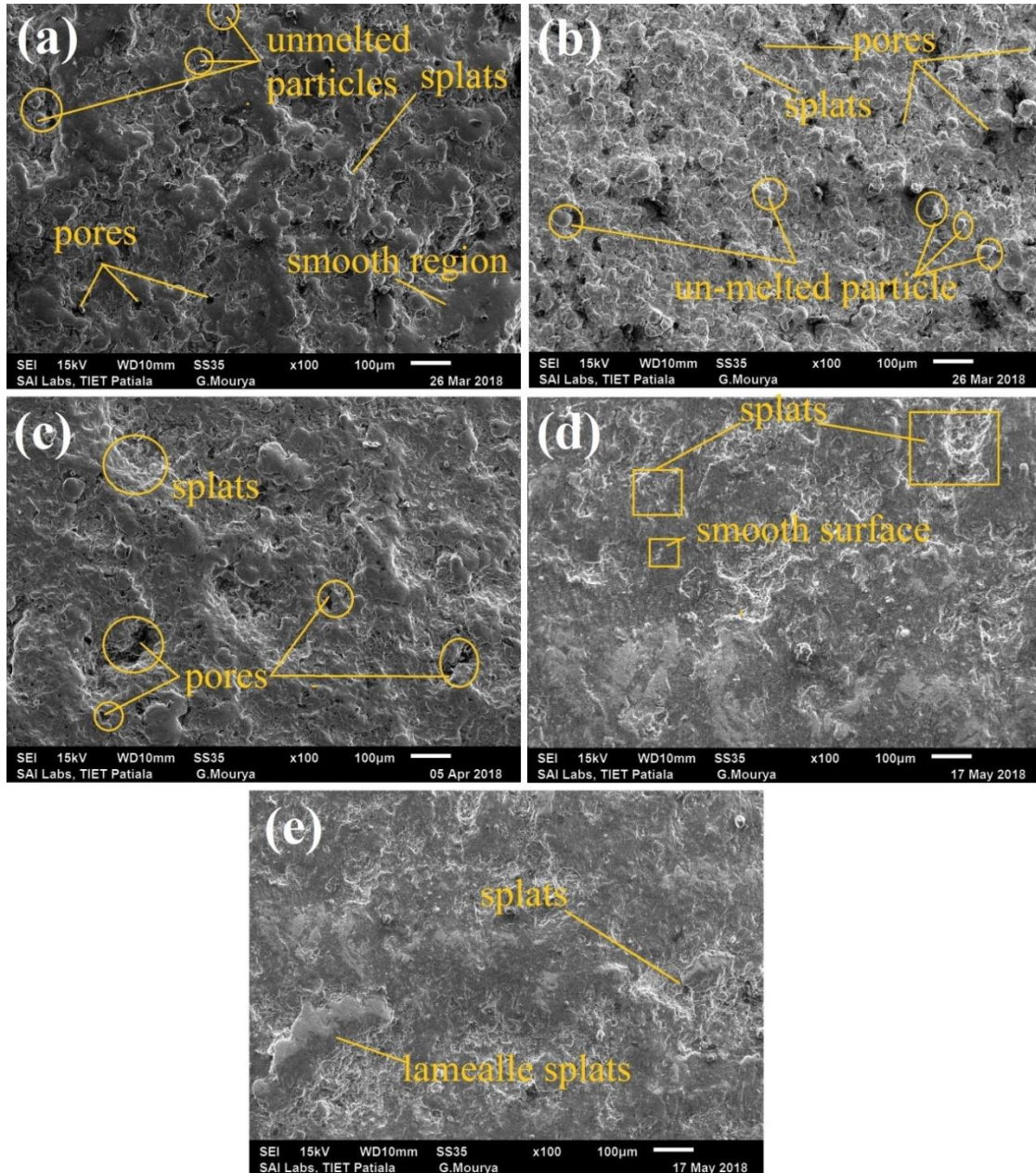


Figure 6.4. SEM micrograph of HVOF sprayed (a) Stellite-6, (b) Colmonoy-88, (c) Ni-20Cr₂O₃, (d) Ni-20Al₂O₃, and (e) Al-20TiO₂ surface.

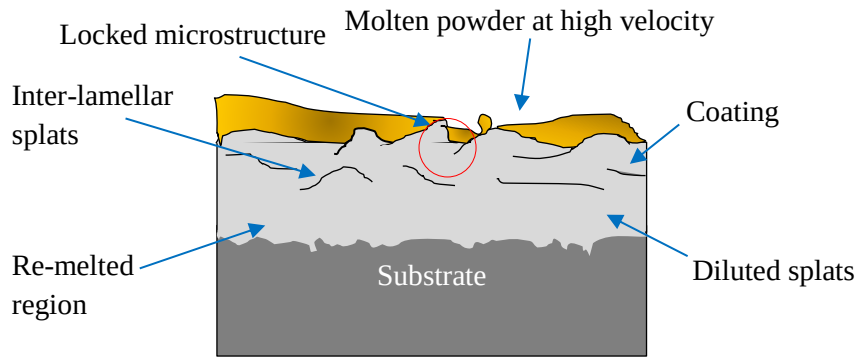


Figure 6.5. Schematic diagram representing development of inter-lamellar splats.

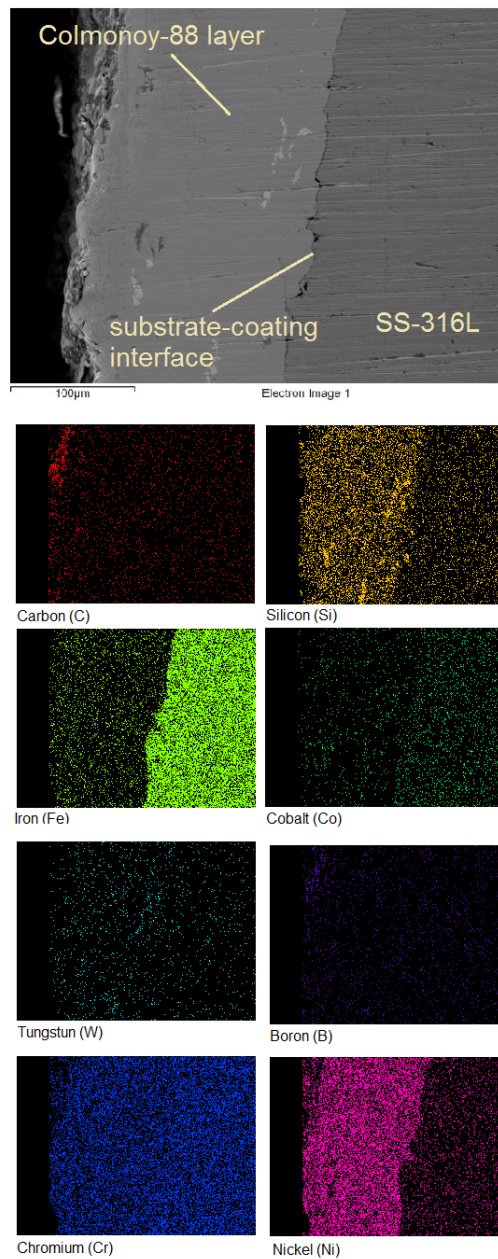


Figure 6.6. EDS mapping of Colmonoy-88 coating.

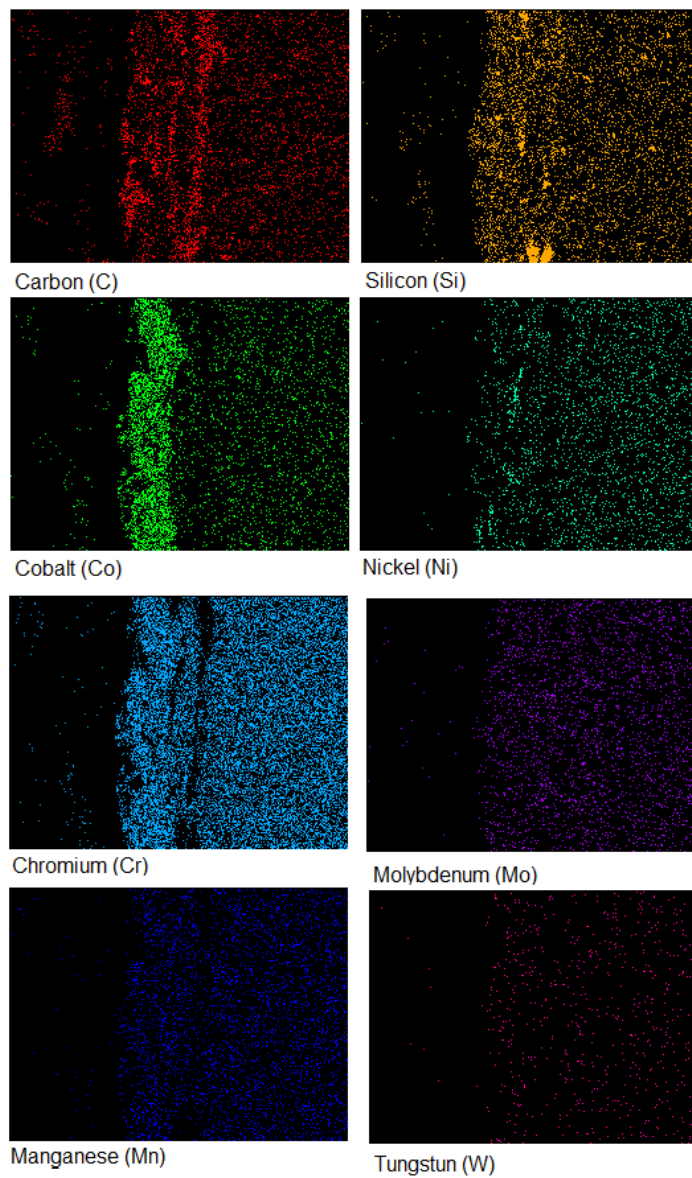
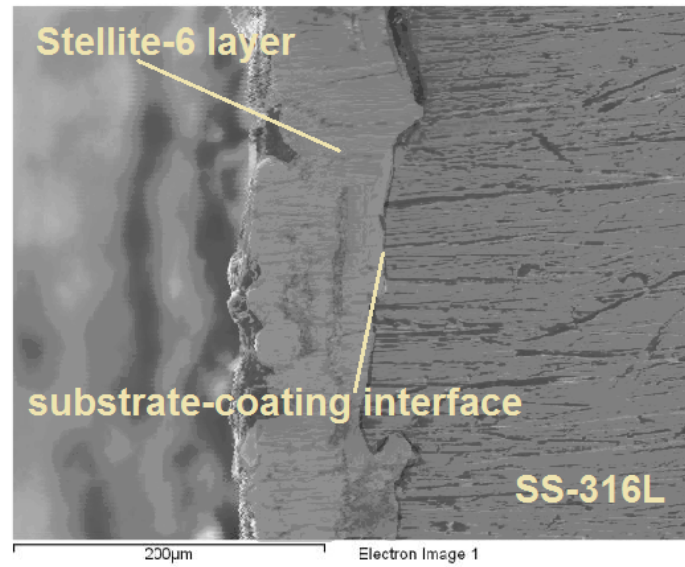
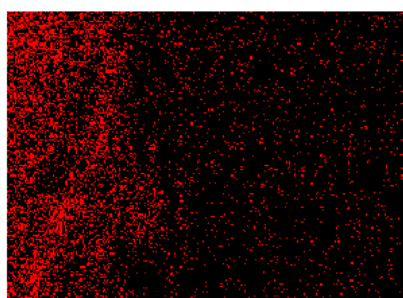
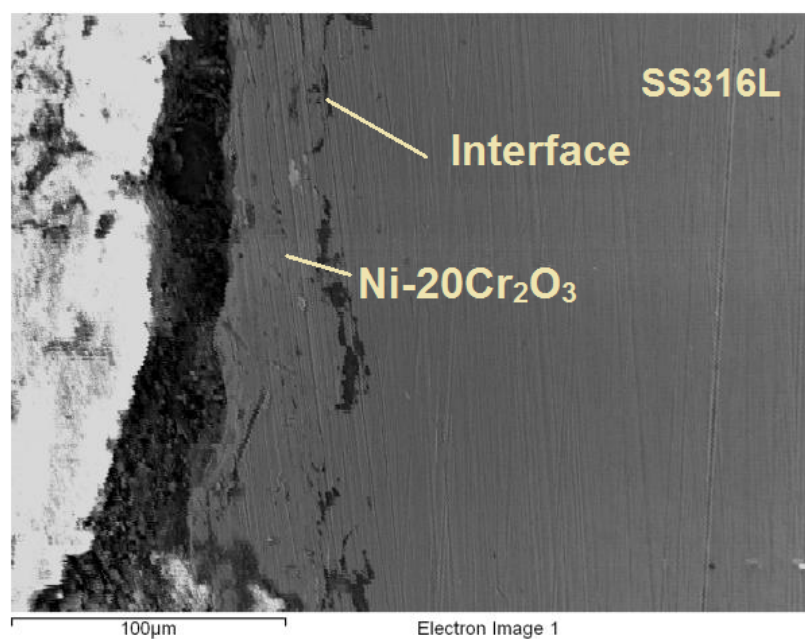
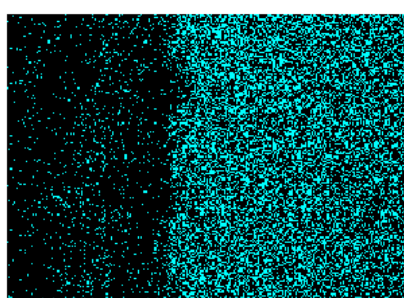


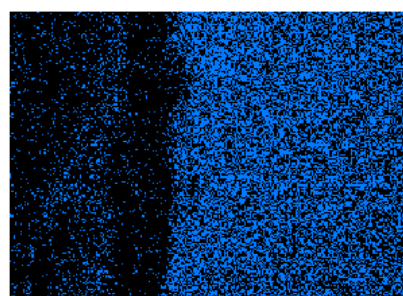
Figure 6.7. EDS mapping of Stellite-6 coating.



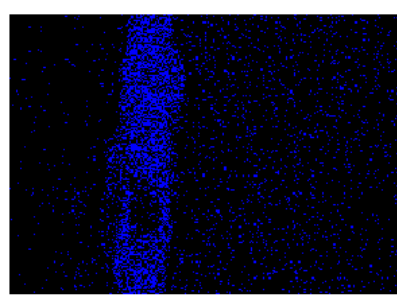
Carbon (C)



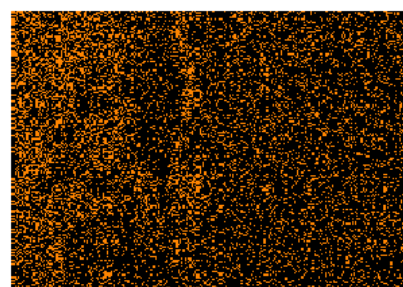
Chromium (Cr)



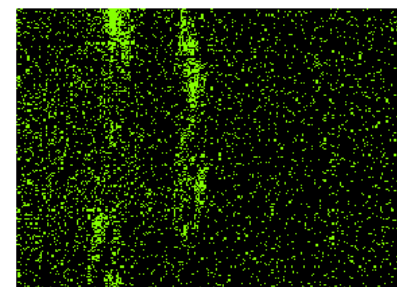
Iron (Fe)



Nickel (Ni)



Oxygen (O)



Silicon (Si)

Figure 6.8. EDS mapping of Ni-20Cr₂O₃ coating.

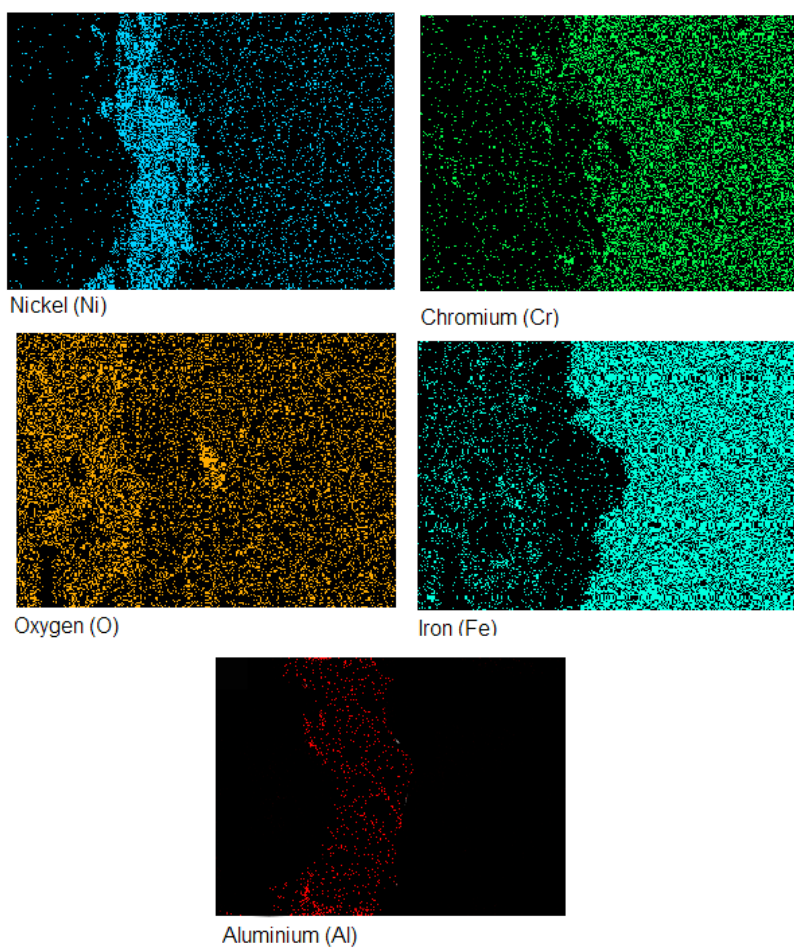
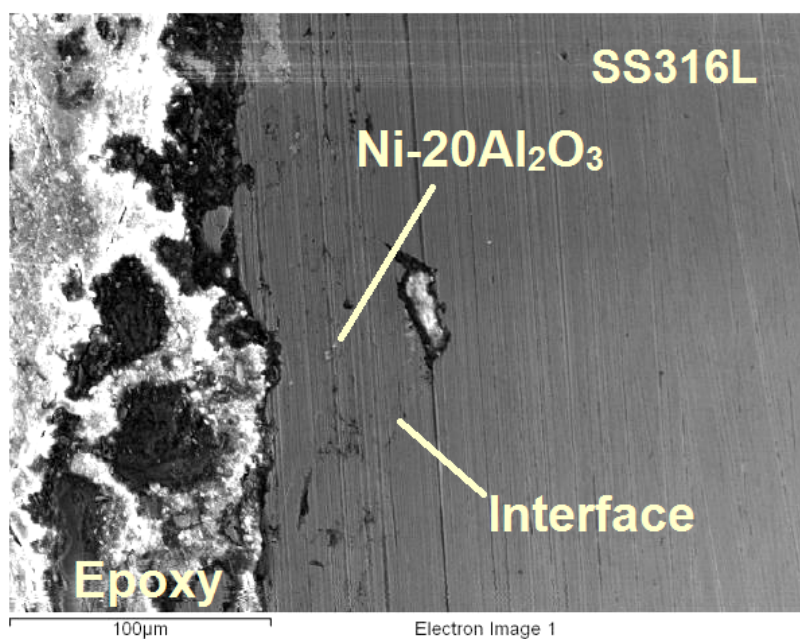


Figure 6.9. EDS mapping of Ni-Al₂O₃ coating.

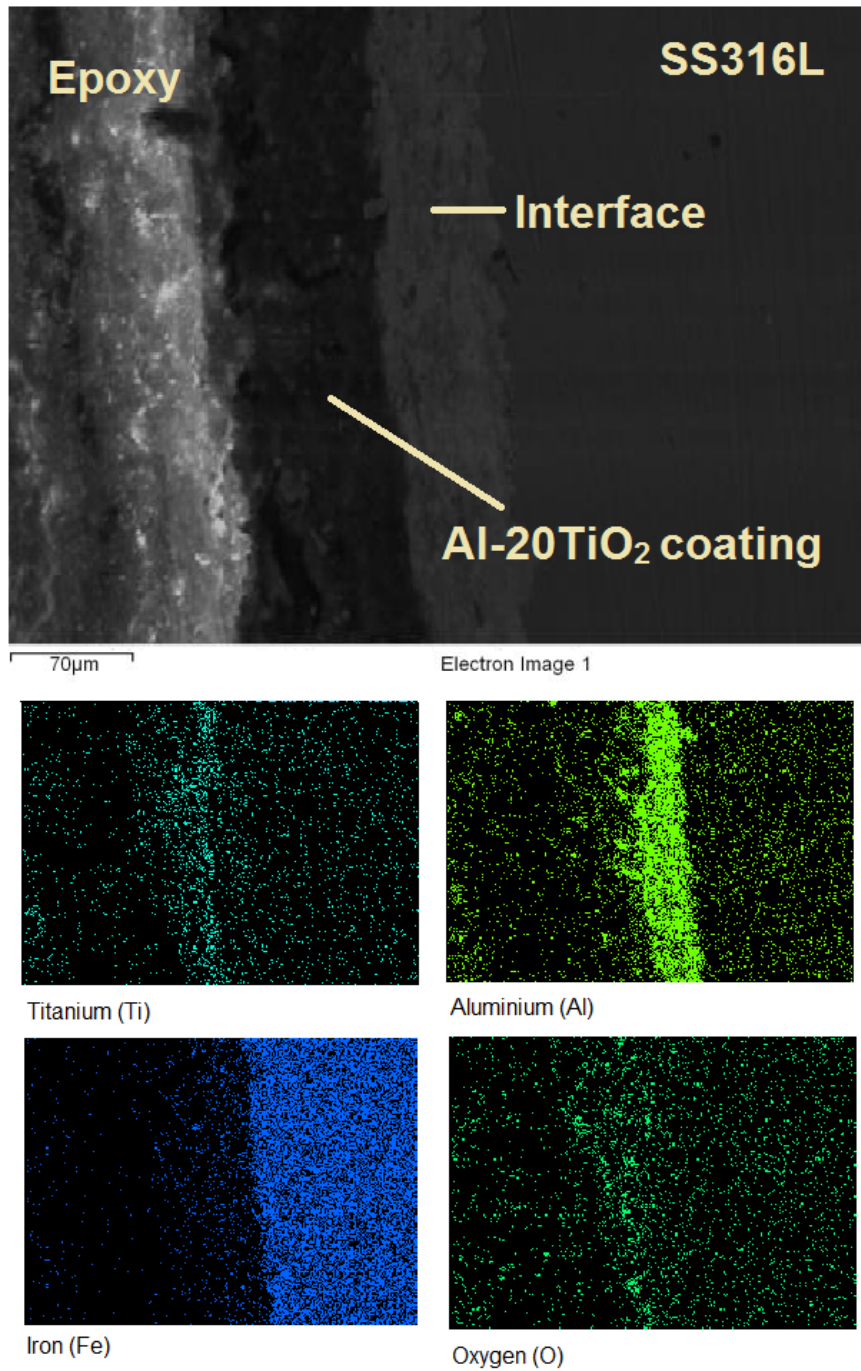


Figure 6.10. EDS mapping of Al-TiO₂ coating.

6.3.3 Cross-sectional surface analysis

The EDS mapping of Colmonoy-88 coating is represented by Figure 6.6. Figure 6.6 confirms the presence of high amount of Nickel (Ni) element in Colmonoy-88. The EDS mapping of Stellite-6 coating is represented by Figure 6.7. Figure 6.7 confirms the presence of high

amount of Cobalt (Co) element in Stellite-6. The transition of elements from coated surface-to-substrate was observed to be uniform which indicates toward high bonding strength at interface. Figure 6.8-6.10 shows the EDS mapping of cross-section of Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ coatings respectively. EDS mapping confirms the presence of high amount of Nickel (Ni) in both of coatings. SS-316L was found to be enriched with Cr element. The smooth transition of elements between coatings and substrates indicate the high bonding strength of both coatings with SS-316L. Coating thickness was also determined by performing SEM on a cross-sectional area of HVOF coated SS-316L. The coating thickness was measured as a random measure of peaks and valleys which was lies in range 190-350 μ m for Colmonoy-88 and Stellite-6 coating. Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ coating were deposited in thickness range of 165-190 μ m on the surface of SS316L.

6.3.4 XRD of as-sprayed surface

The X-Ray diffractometry was carried to examine the crystalline phases formed during the HVOF spraying of Stellite-6, Colmonoy-88, Ni-20Cr₂O₃, Ni-20Al₂O₃, and Al-20TiO₂ coating powders on SS-316L. XRD spectrum of Stellite-6 deposited SS-316L is shown in Figure 6.11. XRD spectra of Stellite-6 show the presence of M₂₃C₆, CoC and Co crystalline phases. XRD spectrum of Colmonoy-88 deposited SS-316L is shown in Figure 6.12. The XRD of Colmonoy-88 reveal that crystalline phase presence of Nickel (Ni and γ -Ni), carbides (WC, CrC, NiC and FeC), ferrite (NiFe₃), boride (Cr₅B₃) crystalline phases. The carbide and boride crystalline phases present in the coatings are brittle and hard phases. Due to this, they enhance the high microhardness to substrate. XRD spectra of Ni-20Cr₂O₃ coated surface reveal the presence of Ni, Ni-Oxide (NiO), Nickel-Chromium oxide (Ni(Cr₂O₄)) and Chromium carbide (Cr₇C₃) crystalline phases, as shown in Figure 6.13. From Figure 6.14, XRD of Ni-20Al₂O₃ coated surface indicate the presence of γ -Ni, Nickel Aluminum (Ni-Al), Nickel oxide (NiO), Nickel-Aluminum oxide (Ni(Al₂O₃)) and Aluminum oxide (Al₂O₃) crystalline phases. Figure 6.15 represents the XRD of Al-20TiO₂ coated surface. It was found that the crystalline phases TiO₂, α -Al₂O₃ and γ -Al₂O₃ were present in Al-20TiO₂ coated surfaces. Phase α -Al₂O₃ was counted as large number of peaks.

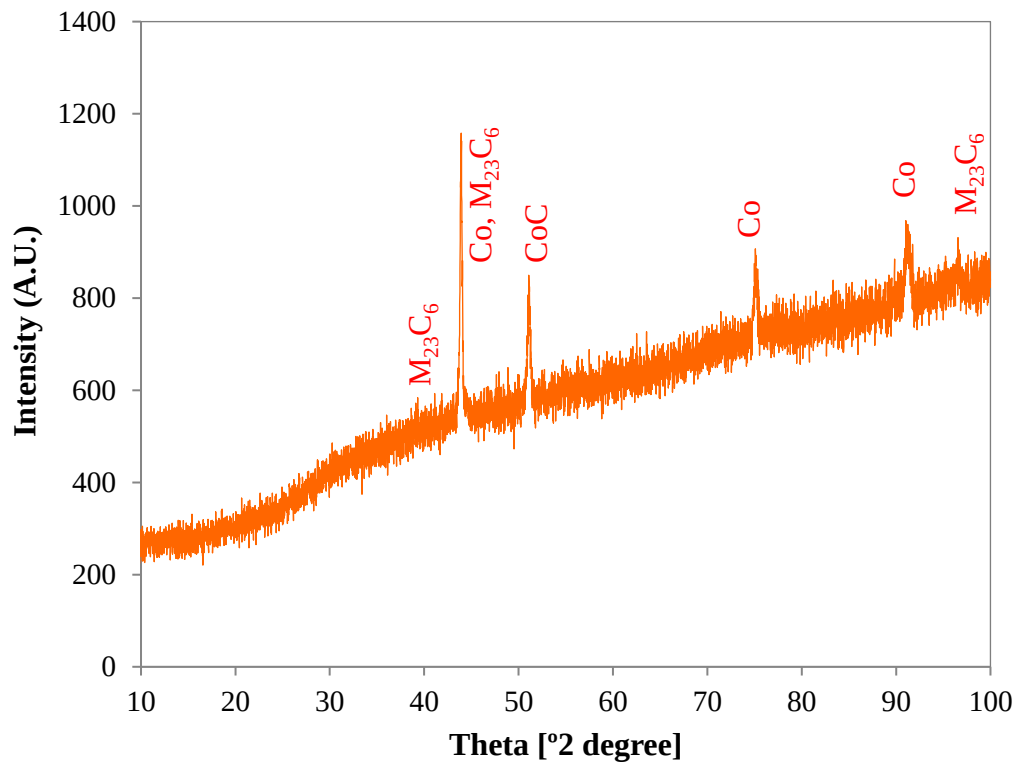


Figure 6.11. XRD of Stellite-6 sprayed surface.

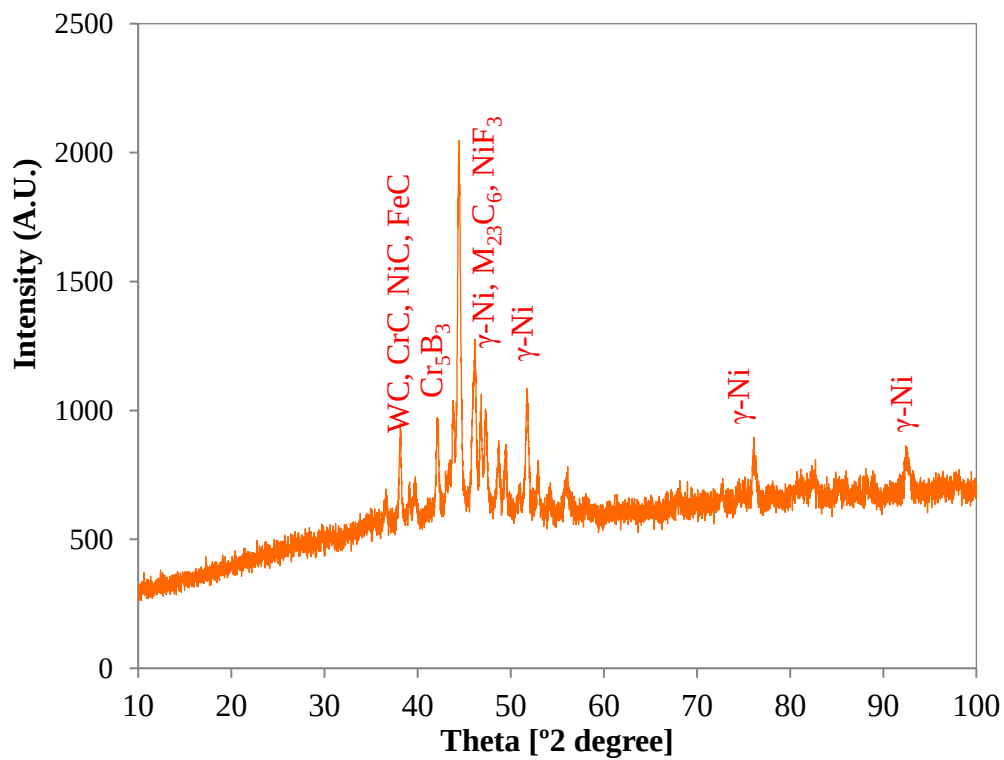


Figure 6.12. XRD of Colmonoy-88 sprayed surface.

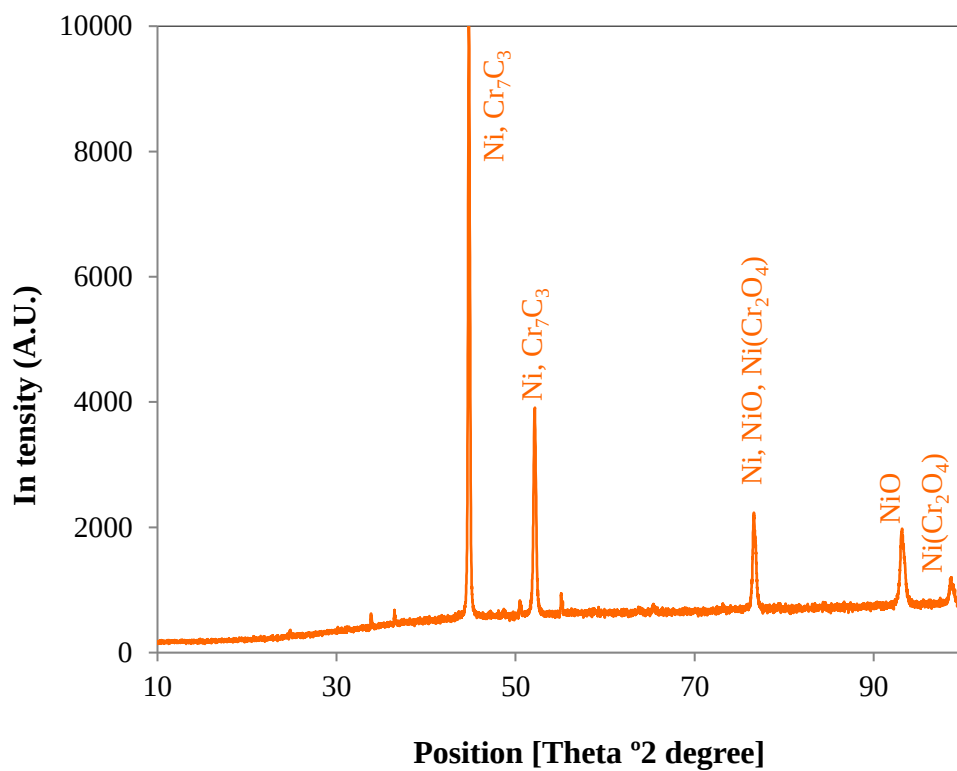


Figure 6.13. XRD of Ni-20Cr₂O₃ sprayed surface.

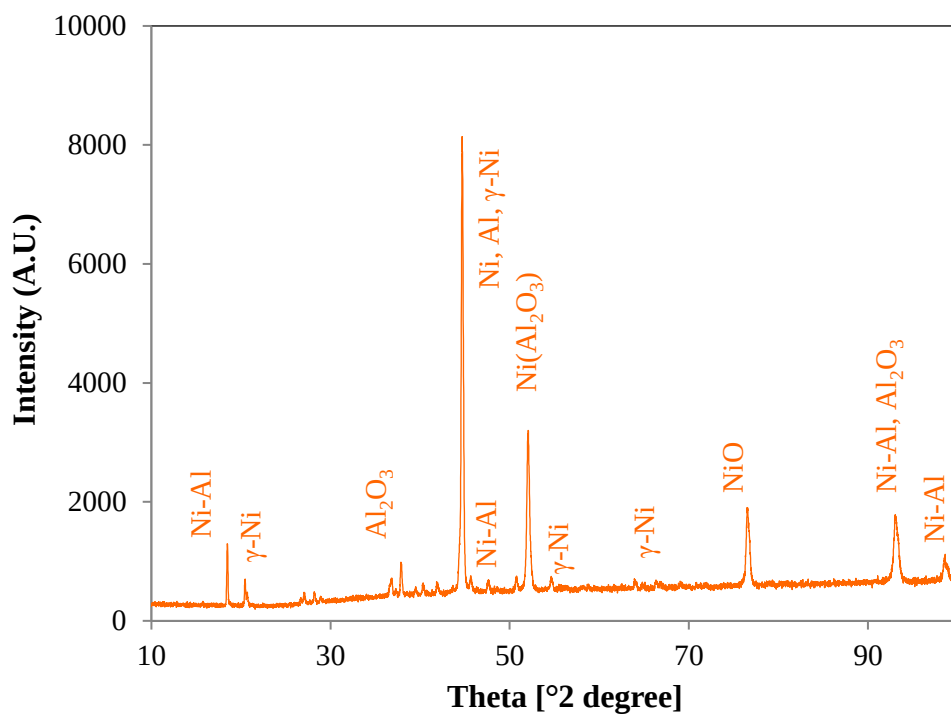


Figure 6.14. XRD of Ni-20Al₂O₃ sprayed surface.

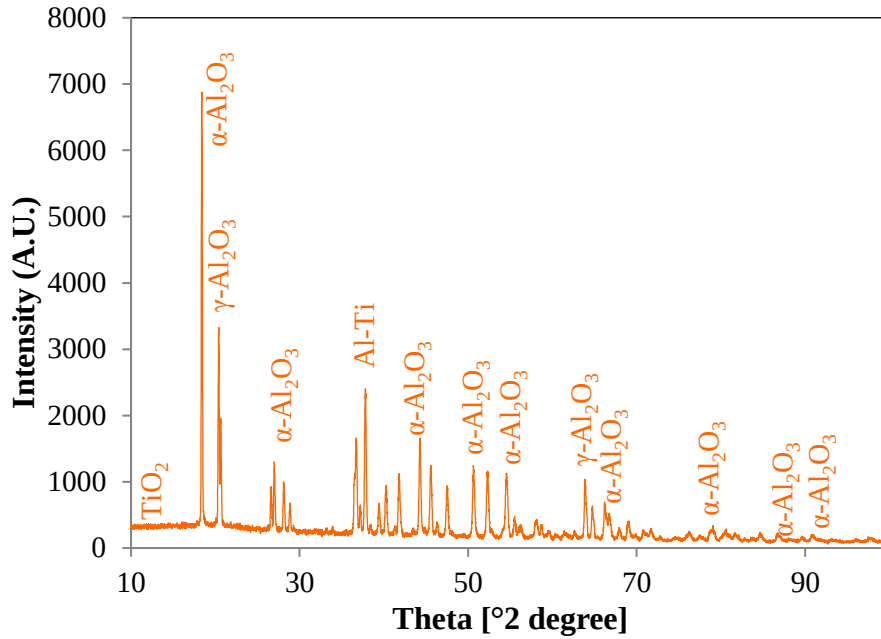


Figure 6.15. XRD of Al-20TiO₂ sprayed surface.

6.3.5 Porosity

The porosity of Colmonoy-88 and Stellite-6 thermal spray coating was analyzed by using the image processing analysis (IPA) technique. By examination, the porosity of Stellite-6, Colmonoy-88, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ coating was found as 1.12, 1.29, 1.46, 1.13 and 1.09% respectively.

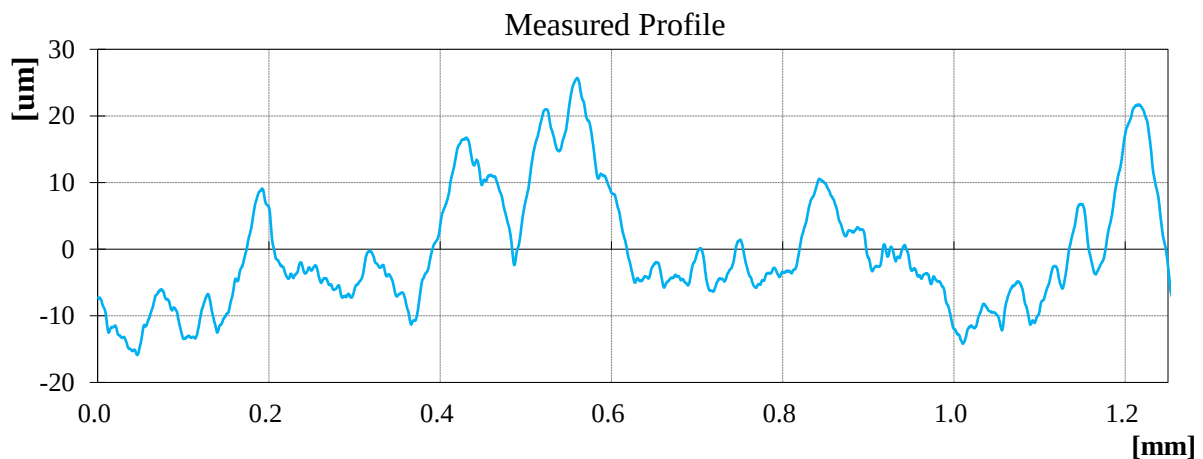


Figure 6.16. Roughness plot of Stellite-6 deposited surface.

6.3.6 Surface roughness analysis

The roughness profile of HVOF deposited Stellite-6 surface for a random testing length of 1.25 mm is shown in Figure 6.16. The average roughness (R_a) of Stellite-6 was found as 5.69

μm . In roughness plots, the values Rq and Rz of Stellite-6 deposited SS-316L were measured to be 6.93 and 31.2 μm respectively. The average roughness of Colmonoy-88 coating was found as 6.67 μm , as shown in Figure 6.17.

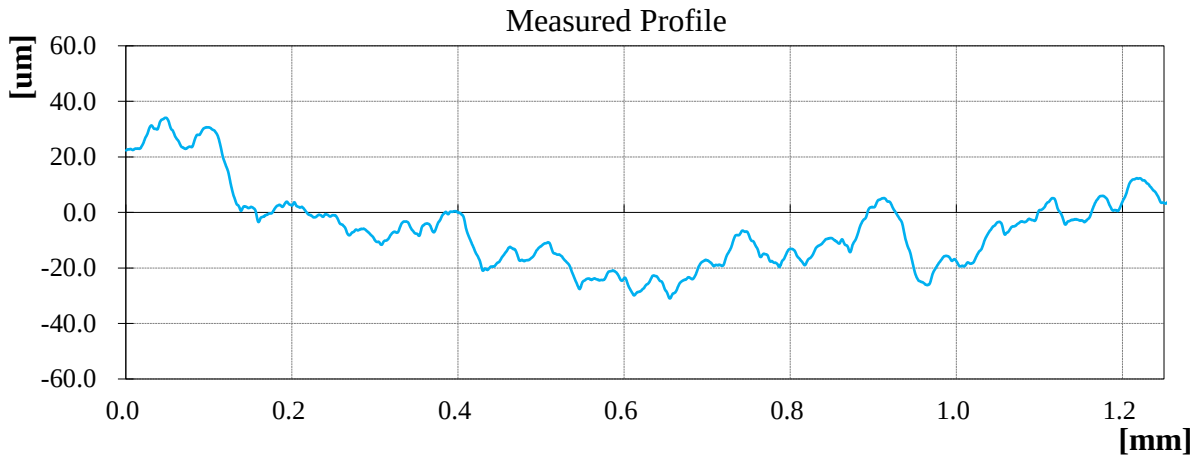


Figure 6.17. Roughness plot of Colmonoy-88 deposited surface.

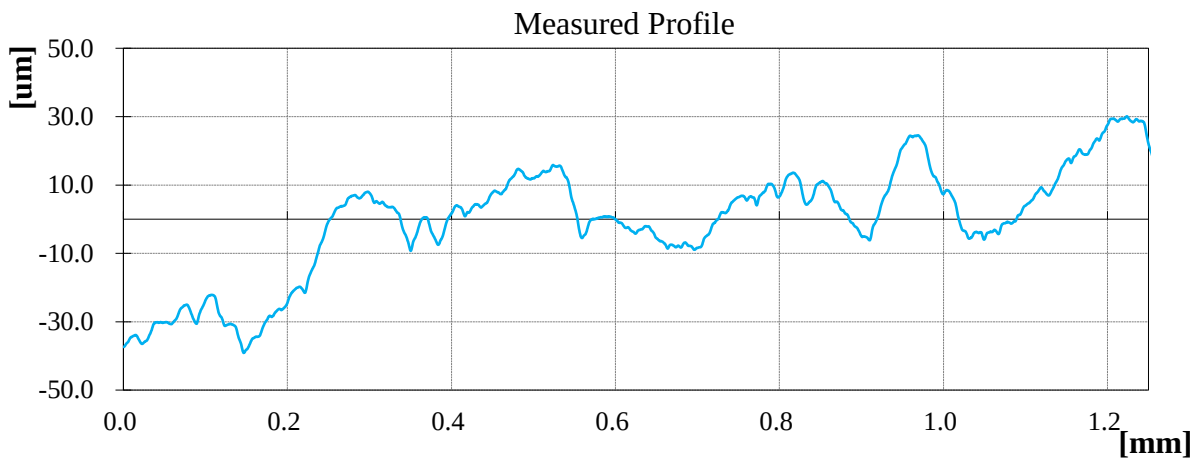


Figure 6.18. Roughness plot of Ni-20Cr₂O₃ deposited surface.

The values Rq and Rz were found as 8.18 and 36.0 μm respectively for Colmonoy-88 coated surface. The average roughness of Ni-20Cr₂O₃ was found as 7.04 μm (Figure 6.18). The values Rq and Rz were measured as 8.49 and 34.6 μm , respectively for Ni-20Cr₂O₃ coated surface. From roughness plots, it can be concluded that the peak-to-depth ratio of Colmonoy-88 coated surface was higher as compared to Stellite-6. The high peaks of Colmonoy-88 deposited surface results in its higher average roughness than Stellite-6 deposited surface. However, the average roughness of Ni-20Cr₂O₃ coated surface was higher as compared to Colmonoy-88 coated surface. Figure 6.19 and 6.20 shows the roughness profiles of Ni-

20Al₂O₃ and Al-20TiO₂ deposited surface. The value of R_a was found as 4.49 and 3.62 μm respectively for Ni-20Al₂O₃ and Al-20TiO₂ coated surface. The values R_q and R_z were measured as 5.32 and 21.3 μm , respectively for Ni-20Al₂O₃ coated surface whereas 4.32 and 18.4 μm , respectively for Al-20TiO₂ coated surface. The order of roughness was found as:

❖ Ni-20Cr₂O₃ > Colmonoy-88 > Stellite-6 > Ni-20Al₂O₃ > Al-20TiO₂.

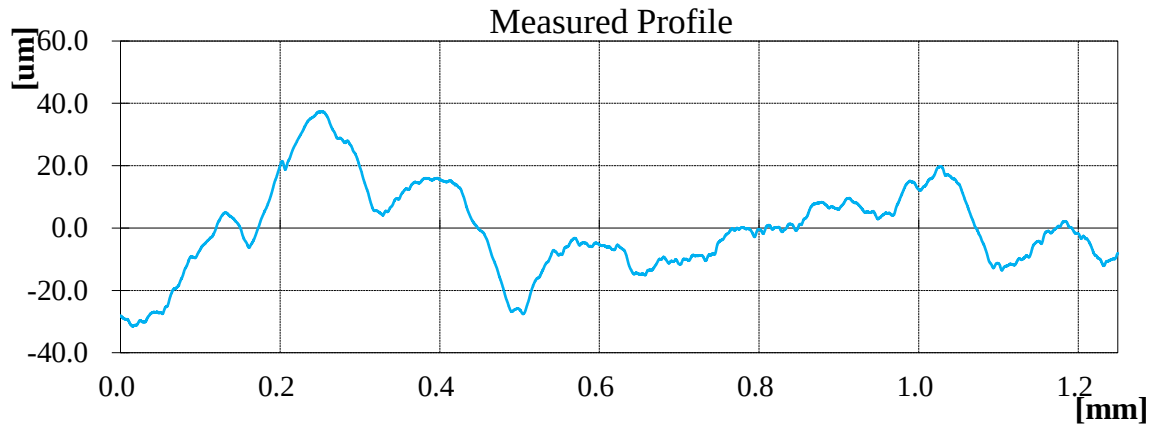


Figure 6.19. Roughness plot of Ni-20Al₂O₃ deposited surface.

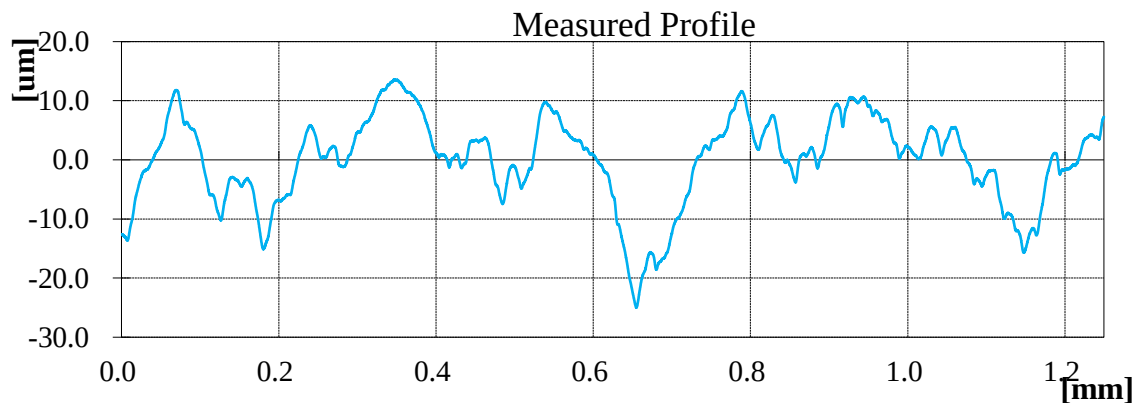


Figure 6.20. Roughness plot of Al-20TiO₂ deposited surface.

6.3.7 Microhardness analysis

Microhardness is an important parameter which contributes majorly in erosion wear. The indents of surface microhardness of coated specimens along the surface are shown in Figure 6.21. The average surface microhardness of Stellite-6, Colmonoy-88, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ deposited SS-316L was found as 449.079, 607.846, 821.014, 315.521 and 291.077 H.V. respectively. Microhardness results of Stellite-6 and Colmonoy-88 shows the close agreement with researchers (Shivamurthy et al. 2009; Kukreja et al. 2012;

Yao, 2014). The reason of high microhardness of Colmonoy-88 is presence of hard carbide and boride crystalline phases which forms after melting and dilution of powder on substrate surface. The order of microhardness was found as:

❖ $\text{Ni-20Cr}_2\text{O}_3 > \text{Colmonoy-88} > \text{Stellite-6} > \text{Ni-20Al}_2\text{O}_3 > \text{Al-20TiO}_2$

The microhardness of coatings was also measured along the vertical axis (along thickness of specimens), represented by Figure 6.22. The average microhardness at substrate-coating interface of Stellite-6, Colmonoy-88, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ deposited SS-316L was measured as 393.865, 537.897, 592.581, 295.354 and 293.317 H.V. respectively.

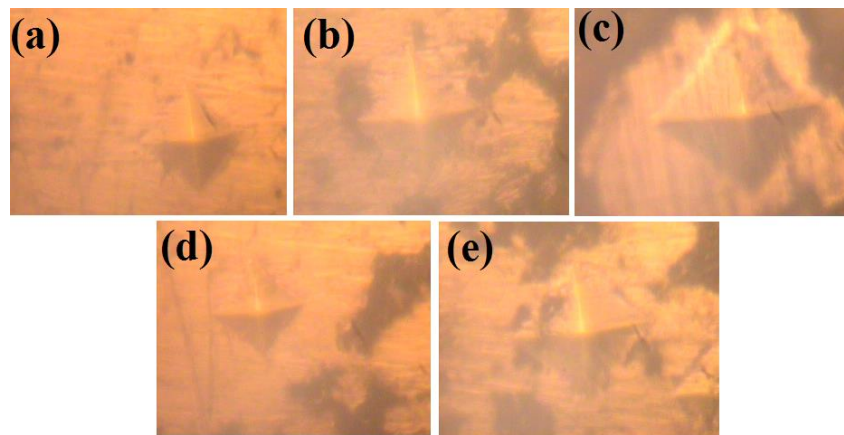


Figure 6.21. Typical indents on the surface of (a) Stellite-6, (b) Colmonoy-88, (c) Ni-20Cr₂O₃, (d) Ni-20Al₂O₃, and (e) Al-20TiO₂ coatings.

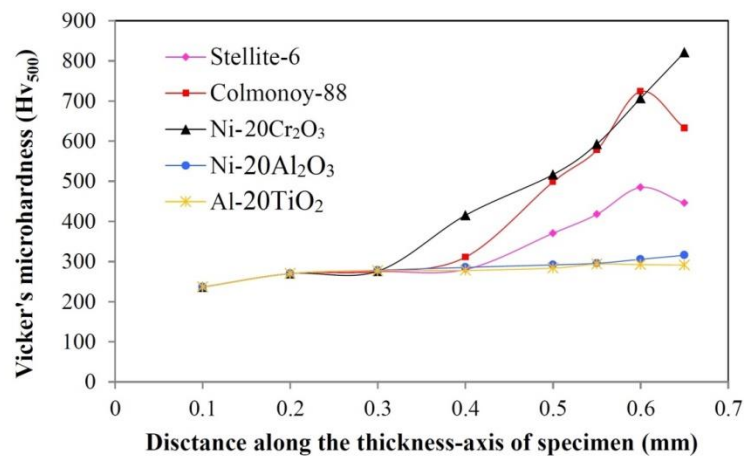


Figure 6.22. Microhardness of coatings measured along the vertical axis (along thickness of specimens).

6.3.8 Mechanical properties of coated surfaces

The fracture toughness of coated surface was examined by using the correlation proposed by

Niihara (1983). The elastic modulus (E) was calculated by generating the true stress-strain curve on tensile testing machine. True stress-true strain curve for HVOF sprayed SS-316L is shown in Figure 6.23. The crack toughness (K_{IC}) of Stellite-6, Colmonoy-88, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ deposited surfaces was found as 19.8 ± 0.56 , 30.1 ± 0.29 , 23.2 ± 0.61 , 1.23 ± 0.82 and 1.83 ± 0.69 MPa.m^{1/2} and respectively.

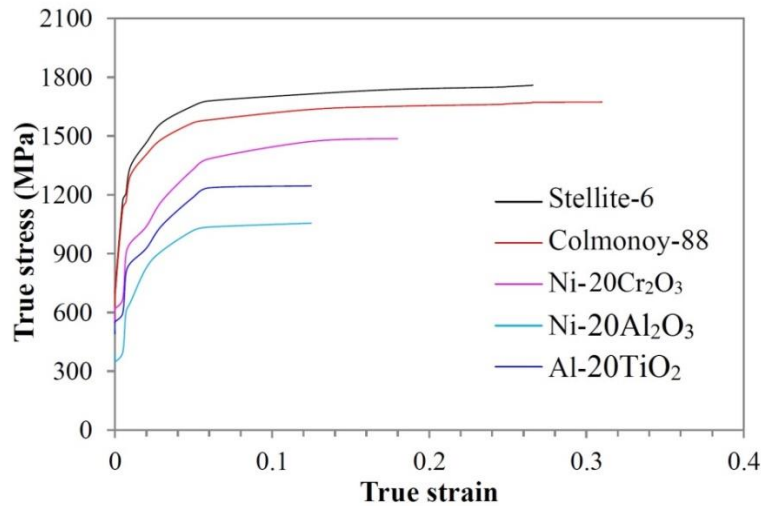


Figure 6.23. True stress-true strain curve for HVOF sprayed SS-316L.

6.4 EROSION WEAR ANALYSIS

6.4.1 Influence of velocity (V) on erosion wear due to different slurries

The erosion wear of different metal composite coatings for different slurries under the influence of rotational speed (N) of propeller has been shown in Figure 6.24. The erosion wear experiments were performed at four different rotational speeds 600, 900, 1200 and 1500 rev/min at solid concentration (C_w) of 30% and time duration (T) of 180 min. Figure 6.244 depicts that the relative erosion wear of specimen increases at non-linear rate with increase in rotational speed of impeller shaft for all slurries. Figure 6.24(a) represents the relative erosion wear of different composite coatings established due to the sand slurry. Colmonoy-88 showed the minimum erosion wear as compared to other coatings. The erosion wear was found as maximum for Al-20TiO₂. Stellite-6 and Ni-20Cr₂O₃ showed least deviation in erosion wear results data. The maximum erosion wear of coatings was found at 1500 rev/min rotational speed of propeller. The maximum erosion wear (at $N = 1500$ rev/min) of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for sand slurry was found as 62.52, 74.67, 74.69, 81.90 and 98.62 gm/m² respectively. The minimum erosion wear of coatings was

found at 600 rev/min rotational speed of propeller. The minimum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for sand slurry was found as 6.51, 9.50, 11.56, 35.44 and 51.65 gm/m² respectively.

- ❖ The order of erosion wear was found as: Colmonoy-88 < Stellite-6 < Ni-20Cr₂O₃ < Ni-20Al₂O₃ < Al-20TiO₂ (for $N = 600\text{-}1500$ rev/min).

The relative erosion wear of different composite coatings established due to the fly ash slurry is represented by Figure 6.24(b). The minimum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for fly ash slurry was found as 2.21, 2.38, 2.76, 3.34 and 4.10 gm/m² respectively. The maximum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for fly ash slurry was found as 3.22, 3.83, 4.99, 6.82 and 8.11 gm/m² respectively. Figure 6.24(c) represents the relative erosion wear of different composite coatings established due to the bottom ash slurry. The order of erosion wear was found similar as erosion wear by sand slurry. The maximum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for bottom ash slurry was found as 50.56, 52.10, 62.29, 68.25 and 82.18 gm/m² respectively. The minimum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for bottom ash slurry was found as 6.19, 9.05, 16.01, 32.74 and 49.19 gm/m² respectively.

6.4.2 Influence of solid concentration (C_w) on erosion wear due to different slurries

Erosion wear of the materials is also affected by concentration of slurry particle. Figure 6.25 shows the erosion wear of different composite coatings with respect to solid concentration. From Figure 6.25, it can be visualized that as the solid concentration increases, the relative erosion wear of all coatings was also increased. The rate of increase in erosion wear was observed as non-linear. Figure 6.25(a) represents the relative erosion wear of different composite coatings established at different solid concentrations of sand slurry. Colmonoy-88 showed the minimum erosion wear as compared to other coatings as observed similar in the previous observation of erosion wear at different rotational speeds. The maximum erosion wear was found at 60% solid concentration (wt.%). The maximum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ at 60% solid concentration of sand slurry was found as 94.143, 104.57, 139.76, 196.61 and 431.57 gm/m² respectively. The minimum erosion wear of coatings was found at 30% solid concentration of sand slurry. The minimum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ at 30% solid concentration of sand slurry was found as 67.55, 60.67, 62.52, 81.90 and 98.62 gm/m² respectively.

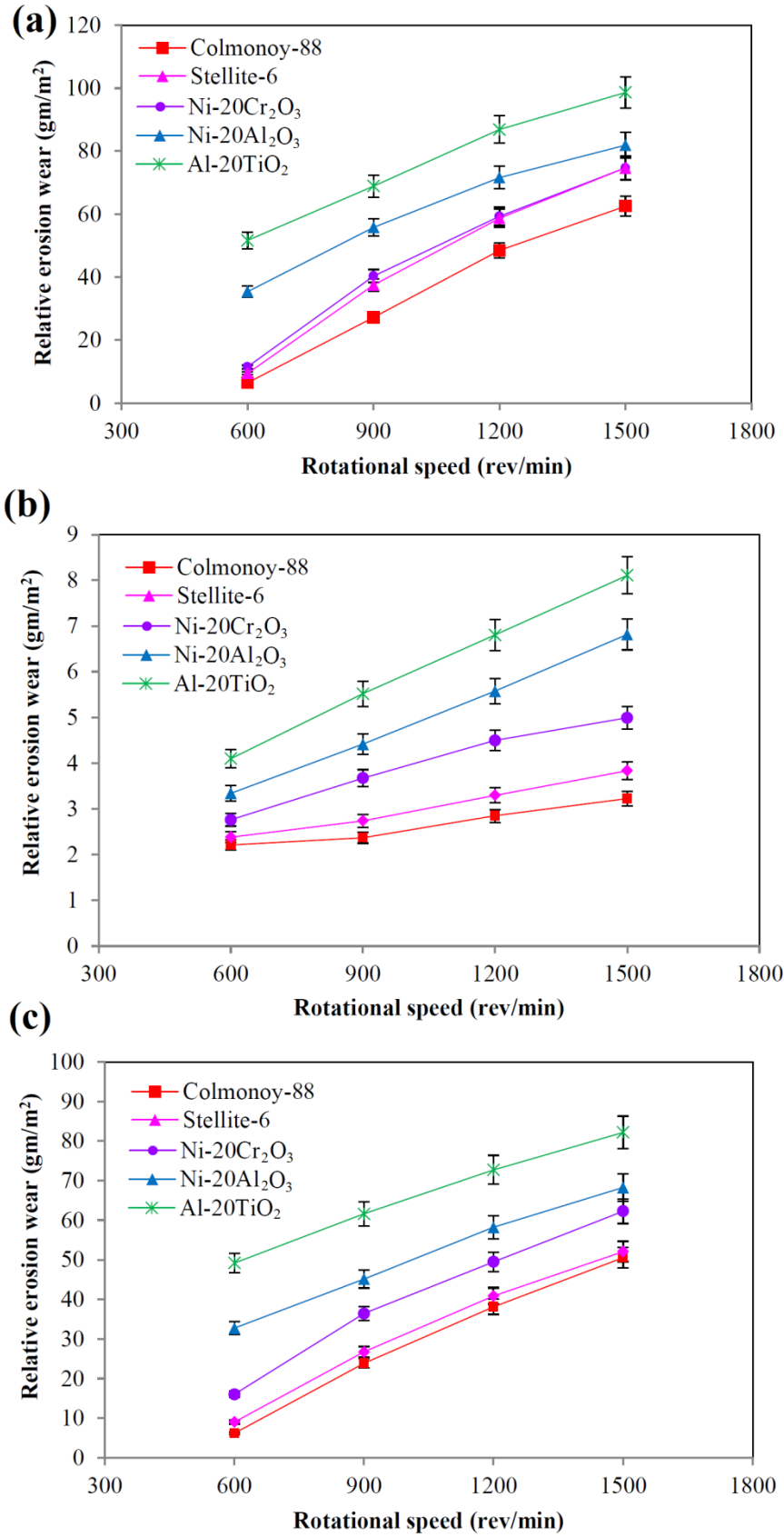


Figure 6.24. Effect of velocity on erosion wear due to (a) sand, (b) fly ash and (c) bottom ash slurries at $C_w = 30\%$ and $T = 180$ min.

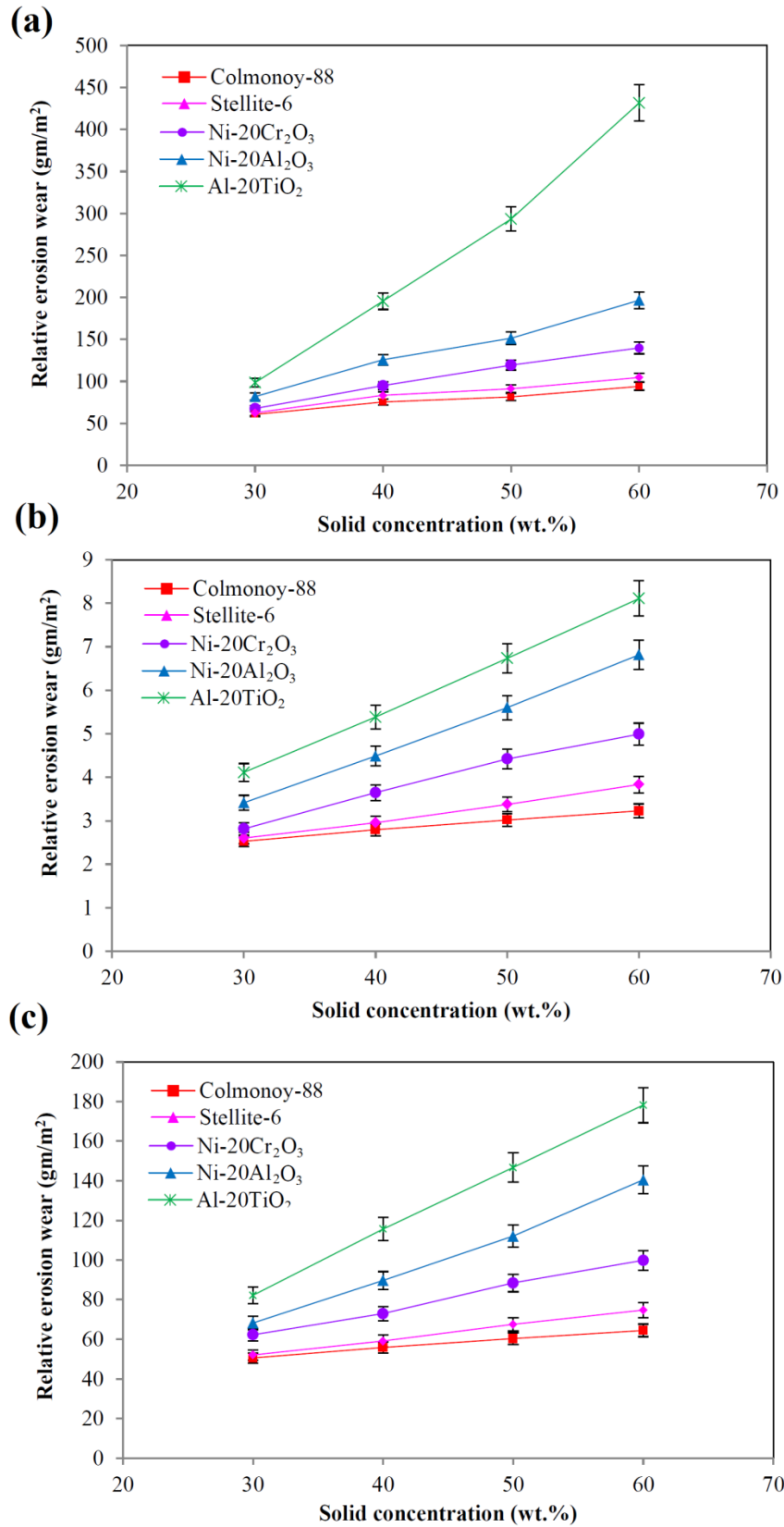


Figure 6.25. Effect of solid concentration on erosion wear due to (a) sand, (b) fly ash and (c) bottom ash slurries at $N = 1500$ rev/min and $T = 180$ min.

The relative erosion wear of different composite coatings established at different solid concentrations of fly ash slurry is represented by Figure 6.25(b). The maximum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for fly ash slurry (at 60% solid concentration) was found as 3.22, 3.83, 4.99, 6.82 and 8.11 gm/m² respectively. The minimum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for fly ash slurry was found as 2.53, 2.60, 2.81, 3.41, and 4.11 gm/m² respectively.

The maximum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for bottom ash slurry (at 60% solid concentration) was found as 64.48, 74.69, 99.83, 140.43 and 178.19 gm/m² respectively, as shown in Figure 6.25(c). The minimum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for bottom ash slurry was found as 50.56, 52.10, 62.29, 68.25 and 82.18 gm/m² respectively. The outcomes of this section are highlighted below:

- ❖ The order of erosion wear for all composite coatings by different slurries was observed as: Sand slurry > Bottom ash > Fly ash.
- ❖ The order of erosion wear was found as: Colmonoy-88 < Stellite-6 < Ni-20Cr₂O₃ < Ni-20Al₂O₃ < Al-20TiO₂ (for $C_w = 30-60\%$).

6.4.3 Influence of time duration (T) on erosion wear due to different slurries

Figure 6.26 shows the relative erosion wear of different coatings for different time duration. The erosion wear experiments were performed for different time durations 90, 120, 150 and 180 min at solid concentration (C_w) of 30% and rotational speed (N) of 1500 rev/min. Figure 6.26 reveals that erosion wear increases with increase in time duration. The maximum erosion wear for sand, bottom ash and fly ash was found for 180 min of time duration. The maximum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ by sand slurry for time duration of 180 min was found as 94.14, 104.57, 139.76, 196.61 and 431.57 gm/m² respectively (as shown in Figure 6.26(a)). The minimum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ by sand slurry for time duration of 90 min was found as 68.19, 74.71, 67.56, 109.82 and 241.07 gm/m² respectively.

The relative erosion wear of different composite coatings established by different time durations for fly ash slurry is represented by Figure 6.26(b). The maximum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for fly ash slurry (at 60% solid concentration) was found as 3.22, 3.83, 4.99, 6.82 and 8.11 gm/m² respectively at 180 min. The minimum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ for fly ash slurry was found as 1.02, 1.23, 1.88, 3.50 and 5.69 gm/m² respectively

at 90 min.

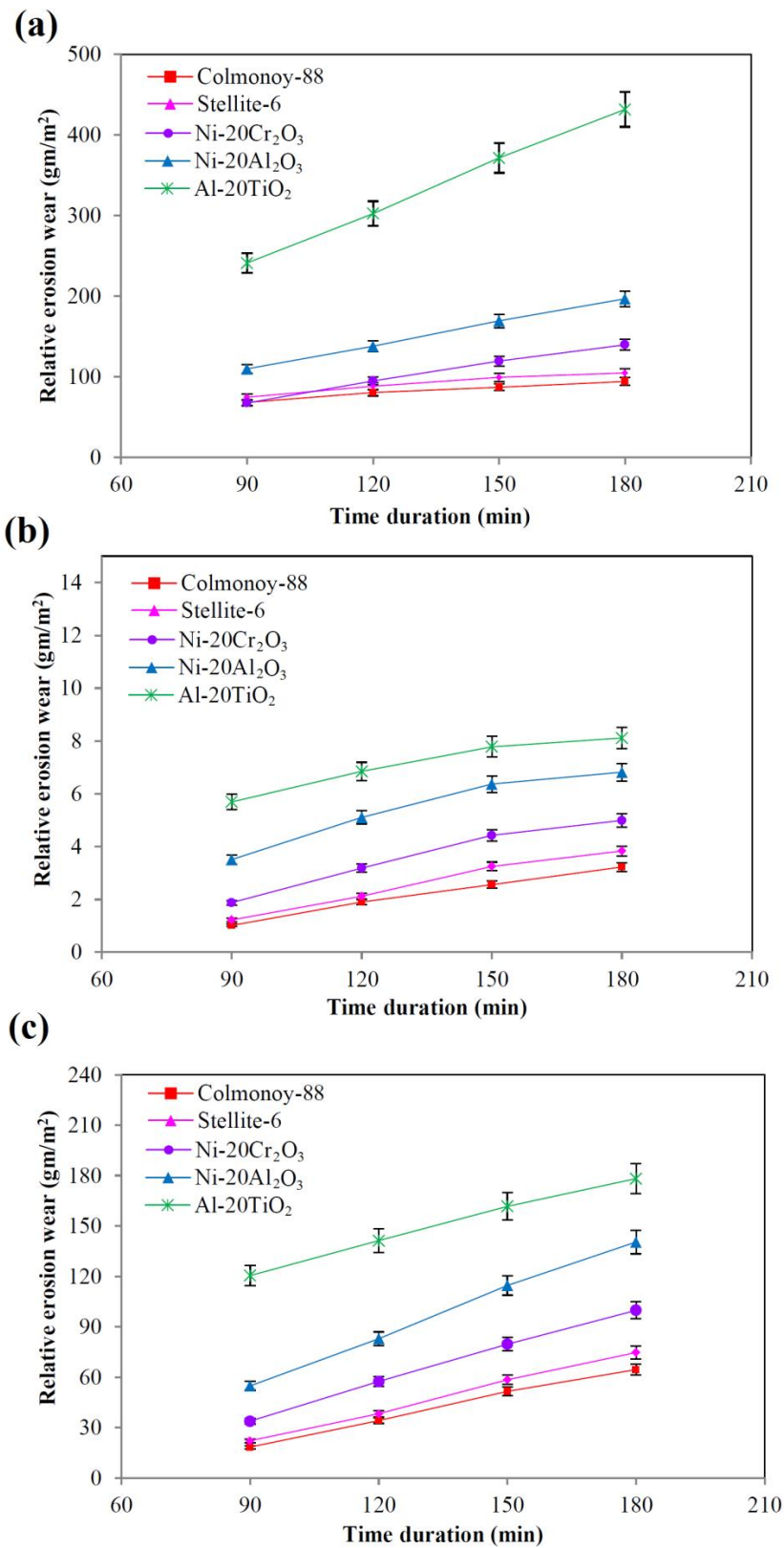


Figure 6.26. Effect of time duration on erosion wear due to (a) sand, (b) fly ash and (c) bottom ash slurries.

The maximum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ by bottom ash slurry for time duration of 180 min was found as 64.48, 74.69, 99.83, 140.4 and 178.19 gm/m² respectively, as shown in Figure 6.26(c). The minimum erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ by bottom ash slurry for time duration of 90 min was found as 18.35, 22.09, 33.78, 54.91 and 120.53 gm/m² respectively.

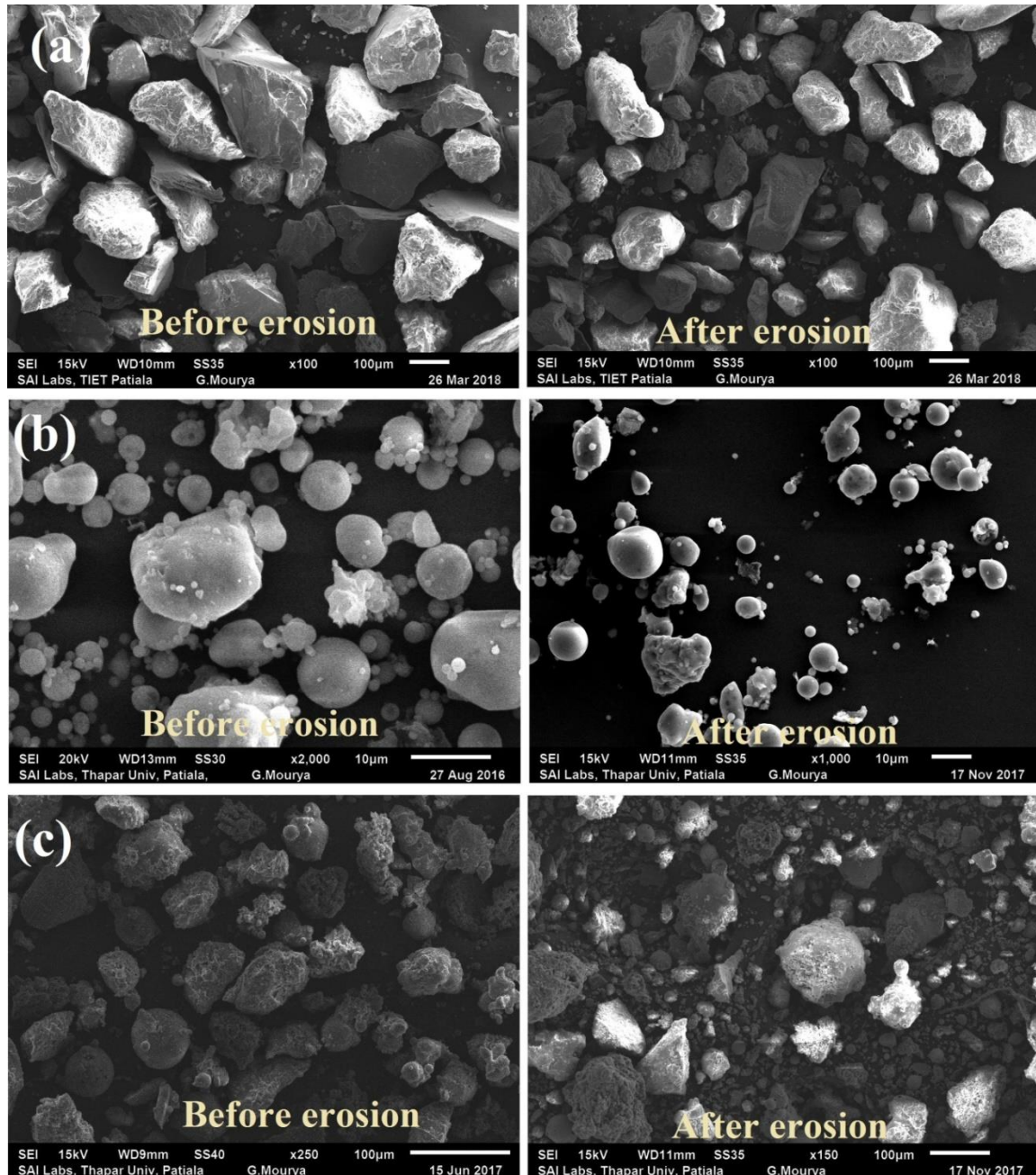


Figure 6. 27. Surface morphology of (a) sand, (b) fly ash and (c) bottom ash particles before and after erosion wear process.

The general observation from graphical data reveals that the increment of erosion wear was

higher during initial phase of experiments. As the time duration increases, the erosion wear increment was found to be decreased. This happened due to a fact that erosion wear process affects the particulate properties. In this context, the bench scale tests were performed on particles after erosion wear experiments. Bench scale tests include the analysis of particle size distribution (*PSD*), circularity factor (*CF*) and surface morphology (using SEM). Surface morphology of particles before and after erosion wear process is represented in Figure 6.27(a). The average *CF* value of multisized sand particles was found to be increased from 0.673 to 0.745. The surface morphology of bottom ash particles before and after erosion wear process is shown in Figure 6.27(b).

Comparative analysis concludes that the size of sand and bottom ash particles decreases after erosion wear experiments. The average *CF* value of multisized bottom ash particles was found to be increased from 0.712 to 0.794 after erosion wear. The physical appearance of particles was affected due to their collisions with specimen which indicates towards chip formation. Also, the change in physical appearance of particles contributes in change of circularity factor (*CF*). On the other hand the, circularity factor of fly ash particles remains almost same, as seen in Figure 6.27(c). It can be said that the *CF* value of irregularly shaped particles increases as they contribute in erosion wear process. Above mentioned facts indicates the implication of change in particulate properties (such as loss of angularity, change in circularity factor, change in particle size etc.) with erosion wear phenomenon. These factors may contribute in decrease of erosion wear after initial phases of experimentation.

6.4.4 Influence of average circularity factor (*CF*) on erosion wear due to different slurries

The erosion wear experiments were performed for different PSD ranges (<75 µm, 75-106 µm, 106-150 µm and >150 µm) to establish the effect of *CF* values. The erosion wear of materials also depends upon the shape of erodent particles. Many of researchers (Bouwman et al. 2004; Woldman et al. 2012; Walker and Humbe, 2015) had mentioned the importance of shape factor in erosion wear phenomenon. An empirical correlation that expresses the dependency of erosion wear on *CF* values is written below (Walker and Humbe, 2015):

$$Er = k \times CF^{-p} \quad (6.1)$$

The CF value of sand particles calculated by image analysis for PSD range of $<75\ \mu\text{m}$, $75-106\ \mu\text{m}$, $106-150\ \mu\text{m}$ and $>150\ \mu\text{m}$ was found as 0.76, 0.65, 0.63 and 0.53 respectively. The equisized slurry was prepared for a particular particle size range of erodent material. The concentration of equi-sized slurry was kept constant i.e. 60% (by weight). The weighing of erodent material was performed with respect to weight of water for preparing a particular concentration. Afterwards, the stirring was done manually. Figure 6.28 shows the effect of circularity factor (CF) on relative erosion wear of coated surfaces. From Figure 6.27, it was observed that as the erosion wear of different coatings was decreased with increase in CF value (Walker and Humbe, 2015). The erosion wear values follow the power-law relationship with CF value. The erosion wear was found maximum at smaller CF value for sand, fly ash and bottom ash slurry.

The erosion of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ was decreased by 2.46, 2.47, 2.42, 2.52 and 2.43 times with increase in CF value of sand particles from 0.53 to 0.76 (as observed in Figure 6.28(a)). The erosion of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ was decreased by 4.85, 12.39, 4.77, 1.79 and 1.76 times with increase in CF value of fly particles from 0.53 to 0.76 (as observed in Figure 6.28(b)). The erosion of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ was decreased by 2.48, 2.47, 2.32, 2.56 and 2.42 times with increase in CF value of bottom ash particles from 0.53 to 0.76 (as observed in Figure 6.28(c)).

6.4.5 Influence of Impact angle (α) on erosion wear due to different slurries

In present study, the relative erosion wear experiments were performed at 0° , 30° , 45° and 60° by developing impact angle arrangements for TR-41 pot tester. Figure 6.29 represents the relative erosion wear of different coatings at different impact angles. The maximum erosion was observed at 30° impact angle arrangement for Stellite-6 and Ni-20Cr₂O₃ coatings whereas at 60° impact angle for Colmonoy-88, Ni-20Al₂O₃ and Al-20TiO₂ coatings.

At $\alpha = 30^\circ$, the relative erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ was found as 100.05, 145.07, 124.96, 198.37 and 466.10 gm/m² respectively (as shown in Figure 6.29(a)). It was found that the Stellite-6 and Ni-20Cr₂O₃ coating shows the ductile erosion wear whereas Colmonoy-88, Ni-20Al₂O₃ and Al-20TiO₂ showed the semi-brittle erosion wear behavior. The order erosion wear of different coatings at different impact angles is written below:

- ❖ Colmonoy-88 < Stellite-6 < Ni-20Cr₂O₃ < Ni-20Al₂O₃ < Al-20TiO₂ (at $\alpha = 0^\circ$).
- ❖ Colmonoy-88 < Ni-20Cr₂O₃ < Stellite-6 < Ni-20Al₂O₃ < Al-20TiO₂ (at $\alpha = 30^\circ$ and 45°).

❖ $\text{Ni-20Cr}_2\text{O}_3 < \text{Colmonoy-88} < \text{Stellite-6} < \text{Ni-20Al}_2\text{O}_3 < \text{Al-20TiO}_2$ (at $\alpha = 60^\circ$).

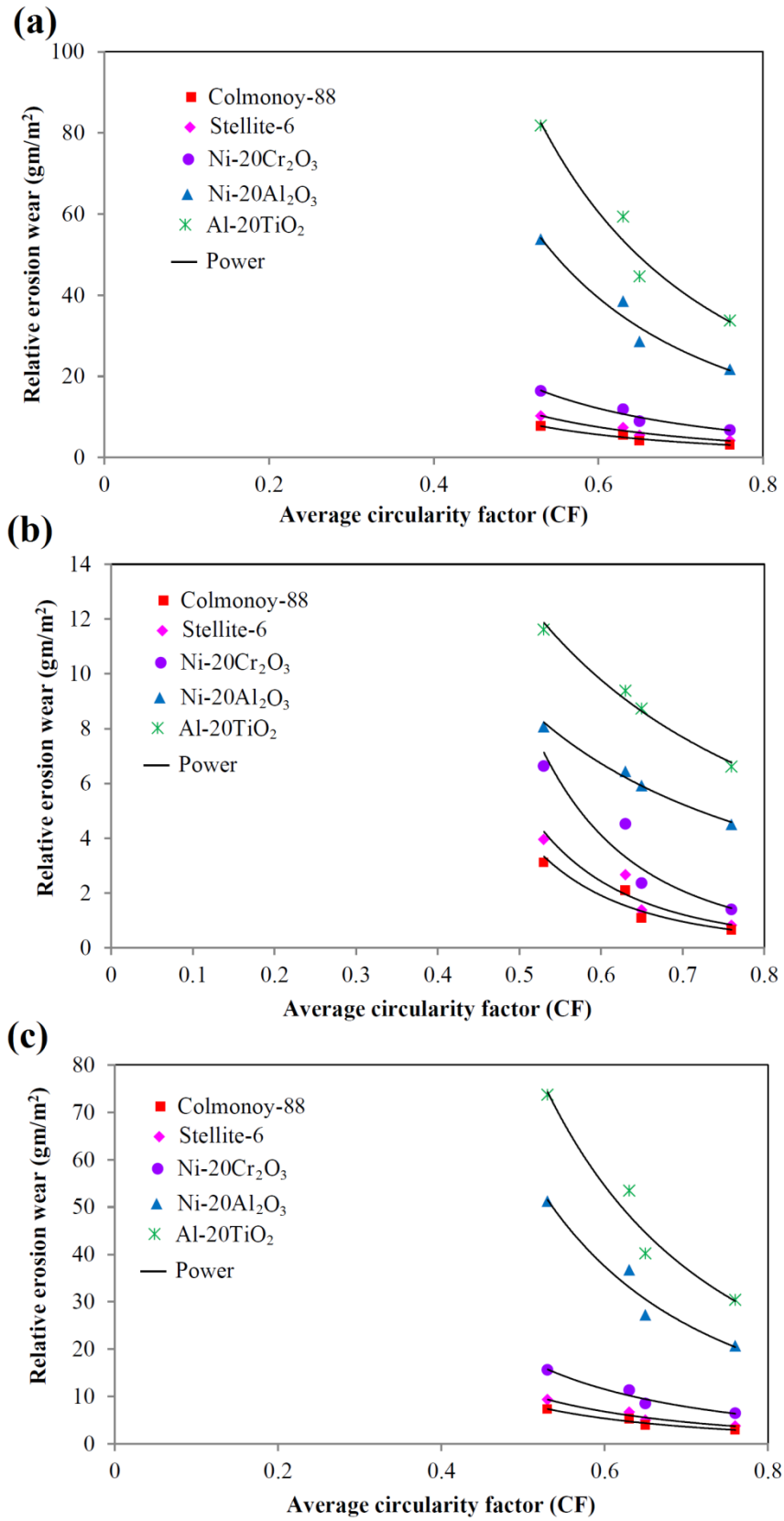


Figure 6.28. Effect of CF value on erosion wear due to (a) sand, (b) fly ash and (c) bottom ash slurries at $C_w = 30\%$ and $N = 600$ rev/min.

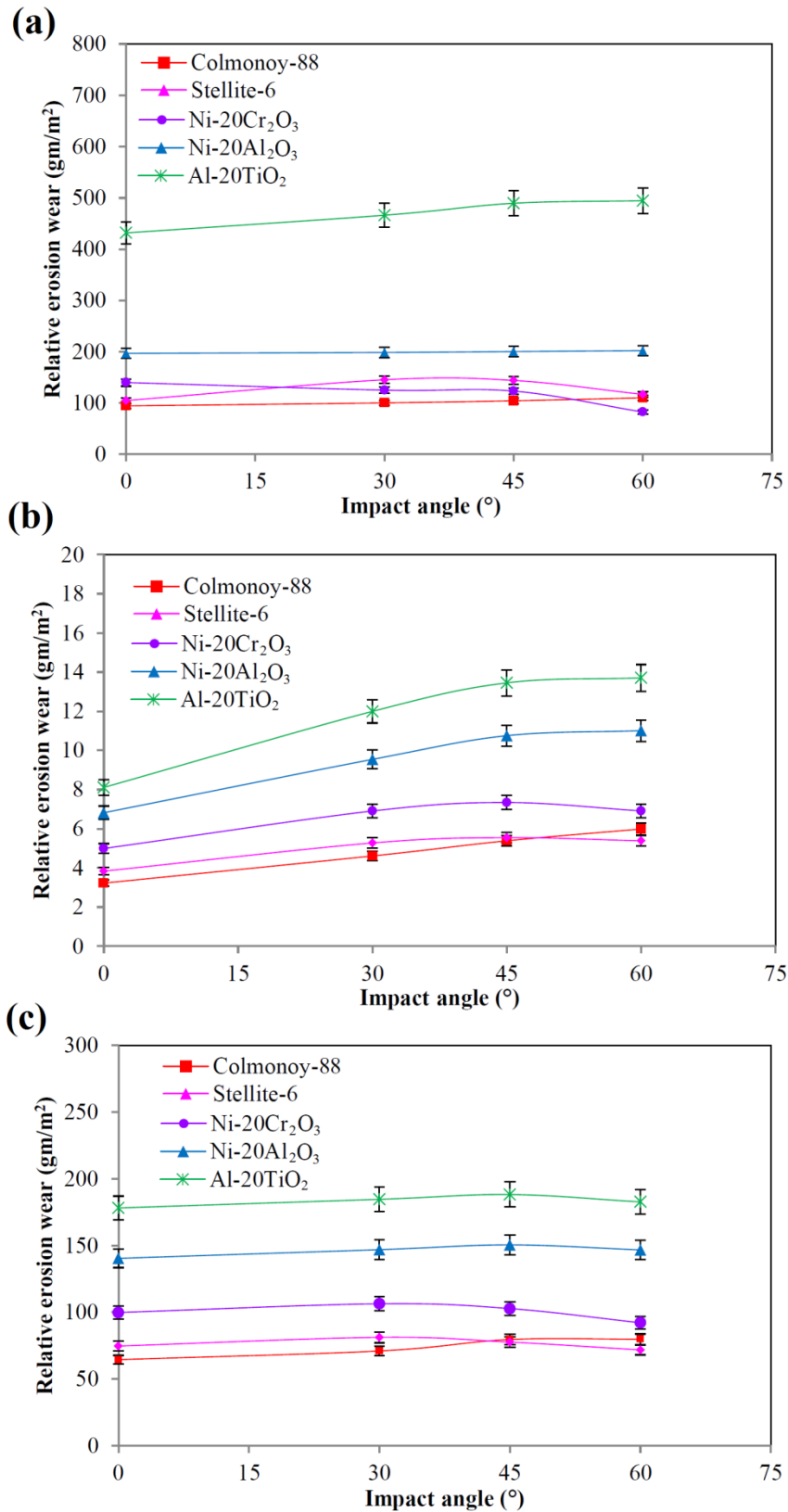


Figure 6.29. Effect of impact angle on erosion wear due to (a) sand, (b) fly ash and (c) bottom ash slurries at $C_w = 60\%$ and $N = 1500$ rev/min.

From Figure 6.29(b), the relative erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ was found as 3.22, 3.83, 4.99, 6.82 and 8.11 gm/m² respectively at $\alpha = 30^\circ$. However, the erosion wear at impact angle of 60° was found as 5.99, 5.38, 6.91, 11.01 and 13.71 gm/m² respectively for Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ coatings. Erosion wear phenomenon remains almost same for fly ash slurry. The order erosion wear of different coatings at different impact angles is written below:

- ❖ Colmonoy-88 < Stellite-6 < Ni-20Cr₂O₃ < Ni-20Al₂O₃ < Al-20TiO₂ (at $\alpha = 0^\circ$).
- ❖ Colmonoy-88 < Stellite-6 < Ni-20Cr₂O₃ < Ni-20Al₂O₃ < Al-20TiO₂ (at $\alpha = 30^\circ$ and 45°).
- ❖ Stellite-6 < Colmonoy-88 < Ni-20Cr₂O₃ < Ni-20Al₂O₃ < Al-20TiO₂ (at $\alpha = 60^\circ$).

Similarly, the erosion wear of due to bottom ash slurry remains at impact angle of 30° was found as 71.01, 81.22, 106.36, 146.96 and 184.72 gm/m² for Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ coatings, as represented in Figure 6.29(c). The erosion wear of Colmonoy-88, Stellite-6, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ coatings was found as 79.84, 71.79, 92.16, 146.79 and 182.75 gm/m² respectively at impact angle of 60° . The order of erosion wear was found same as observed for sand slurry. Al-20TiO₂ could not be recommended for erosion wear experiments.

6.5 MICROSTRUCTURE ANALYSIS OF ERODED COATINGS

The eroded surface of different coatings was characterized from wear mechanisms obtained from SEM micrographs. The failure occurs due to erosion wear depend upon the type of material, process parameters and properties of erodents. Impact is a crucial parameter that decides the type of erosion wear. Researchers (Bitter, 1963(a, b); Clark and Hartwich, 2001; Mann and Arya 2001) reported that chipping and microcutting occurs at low impingement angles. Researchers (Manisekaran *et al.* 2007; Clark and Hartwich, 2001, Turenne *et al.* 1990) discussed that craters and ploughing action takes place at high impact angles. Erosion wear mechanisms depend upon the type of material (i.e. ductile, brittle or elastic), impingement angle, velocity of particles, size and shape of particles, etc. Many of the researchers (Sharma *et al.* 1972; Elkholy, 1983; Gandhi *et al.* 2003; Manisekaran *et al.* 2007; Geng *et al.* 2016) have described the erosion wear mechanisms on the basis of impingement angle. Generally, chipping and microcutting action of erosion wear takes place at low impingement angles. On the other hand, crater and ploughing action takes place at high impact angles which results in fatigue failure process (Manisekaran *et al.* 2007).

6.5.1 Microstructure of eroded Colmonoy-88 coatings

The wear mechanisms on eroded surfaces at different impact angles made with sand particles are specified in Figure 6.30. From Figure 6.30, Colmonoy-88 surface underwent to narrow craters due to presence of borides and carbides. A narrow area was seemed to be ploughed at $\alpha = 0^\circ$. The pseudo-color topographic image of Colmonoy-88 eroded at $\alpha = 0^\circ$ is shown in Figure 6.30(a). Microcutting action can be observed by small blue dots. At $\alpha = 30^\circ$, eroded surface of Colmonoy-88 showed the appearance of carbide pullout, fractures and intact, as seen Figure 6.30(b). Hard carbide and boride phases underwent to pullout and fracture mechanisms. Colmonoy-88 shows almost same mechanism (i.e. carbide pull-out and fractures) as at $\alpha = 30^\circ$, as shown in Figure 6.30(b). No lip formation was observed in case of Colmonoy-88 which indicates surface was directly fractured after continuous impingement of sand particles and happening of poor microcutting action. Figure 6.30(c) shows the presence of un-removed splats. Major sections were ploughed and few craters were observed with lip formation. Figure 6.30(d) shows the large carbide fracture on the Colmonoy-88 surface. Size of fractures were comparatively larger than that at $\alpha = 45^\circ$. Brittle erosion wear deals with micro-fractures, pullouts, splat removal and cracking (Geng et al. 2016). From experimental data, it is very tough to decide that the erosion wear of Colomony-88 was either brittle or ductile. However, the Colomony-88 surface underwent to craters with ploughed regions, intact regions, brittle carbide fractures, and carbide pull-outs. The microstructure of erosion wear failure mechanisms occurred on the surface of the Colmonoy-88 coating for fly and bottom ash slurry is shown in Figure 6.31 and 6.32.

6.5.2 Microstructure of eroded Stellite-6 coatings

The wear mechanisms on eroded surfaces of Stellite-6 coatings by sand slurry are specified in Figure 6.33. From Figure 6.33(a) the cratered sections can be visualized in SEM micrographs. From Figure 6.33(b), Stellite-6 surface showed microcutting and ploughing mechanisms of erosion wear at $\alpha = 30^\circ$. The ploughed marks were deeper and randomly distributed on the Stellite-6 surface. Figure 6.33(c) indicates the ploughing action and formation of large craters on the surface of Stellite-6 at $\alpha = 45^\circ$. Presence of smear region shows the melting of loosely bonded particles. At $\alpha = 60^\circ$, the erosion in Stellite-6 was decreased in an extent as compared to 45° impact angle. Figure 6.33(d) shows the presence of un-removed splats. Major sections were ploughed and few craters were observed with lip formation. The erosion wear mechanisms observed on the surface of Stellite-6 were seems to be ductile in nature. The ductile erosion wear deals with mechanisms such as microcutting,

plastic deformation, craters and ploughing, as discussed by many researchers (Gandhi et al. 2003; Manisekaran et al. 2007; Geng et al. 2016). The microstructure of erosion wear failure mechanisms occurred on the surface of the Stellite-6 coating for fly and bottom ash slurry is shown in Figure 6.34 and 6.35.

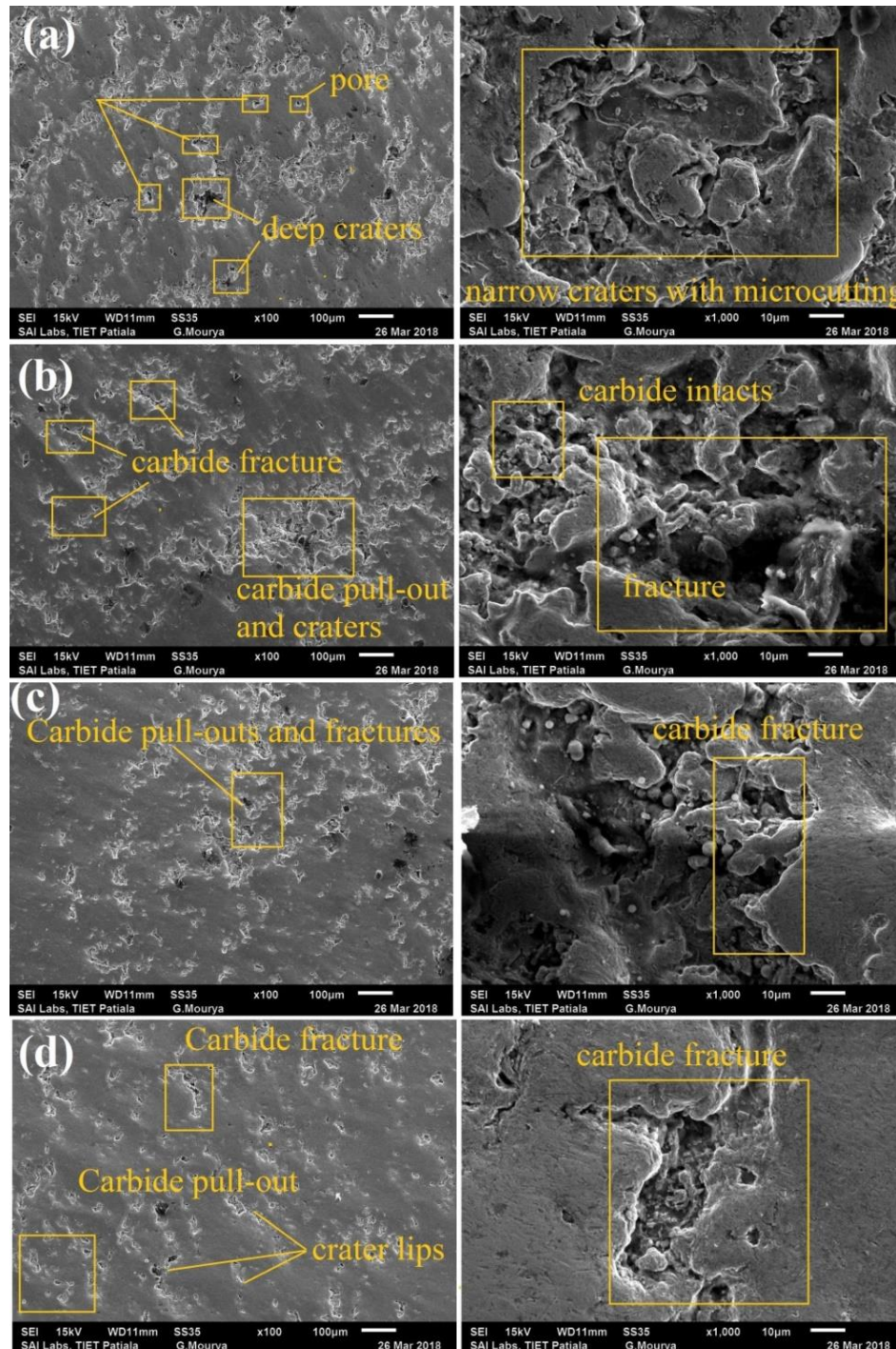


Figure 6.30. Erosion wear mechanism of Colmonoy-88 coating at impact angle of (a) 0°, (b) 30°, (c) 45°, and (d) 60°; for sand slurry.

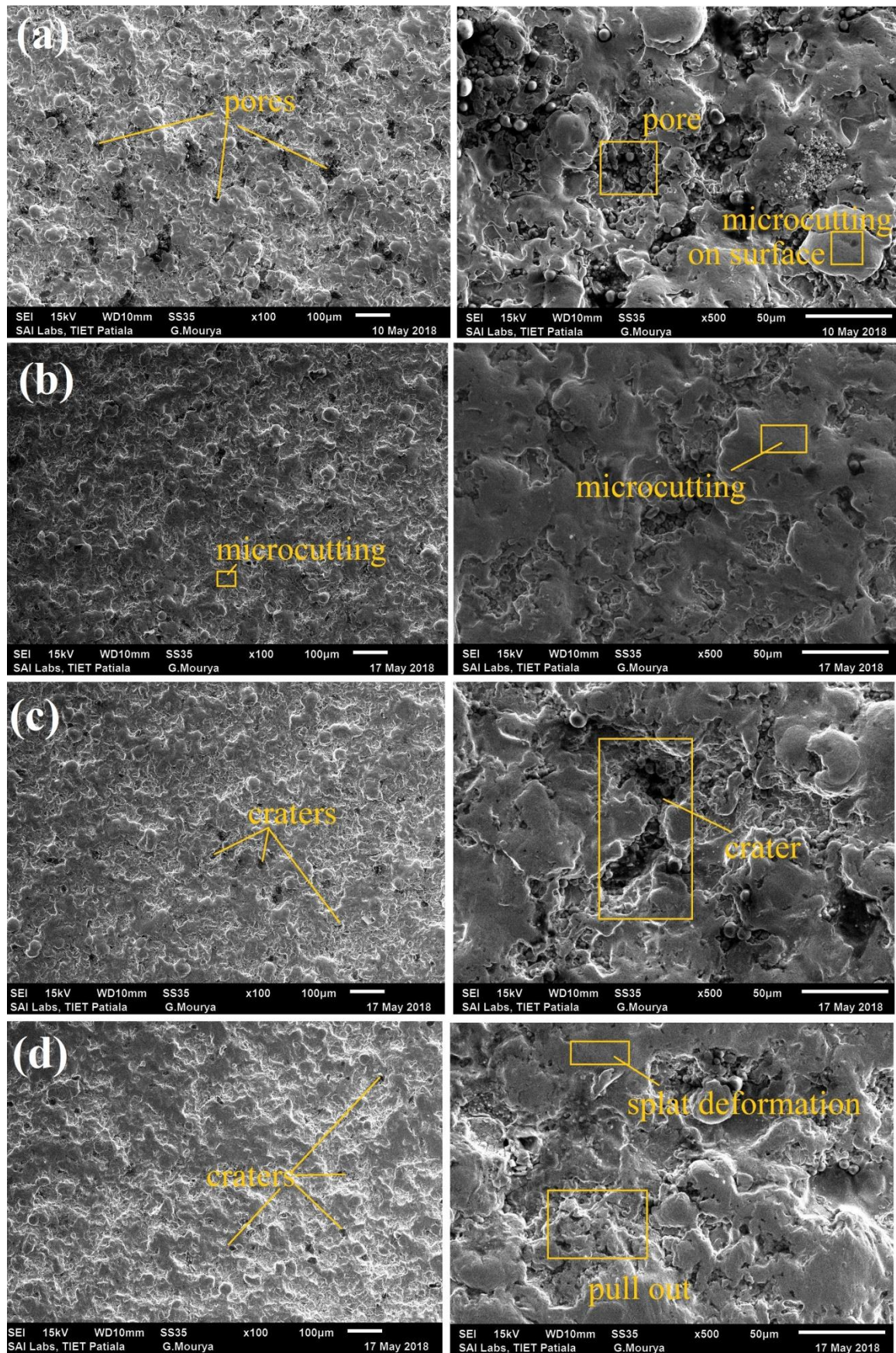


Figure 6.31. Erosion wear mechanism of Colmonoy-88 coating at impact angle of (a) 0°, (b) 30°, (c) 45°, and (d) 60°; for fly ash slurry.

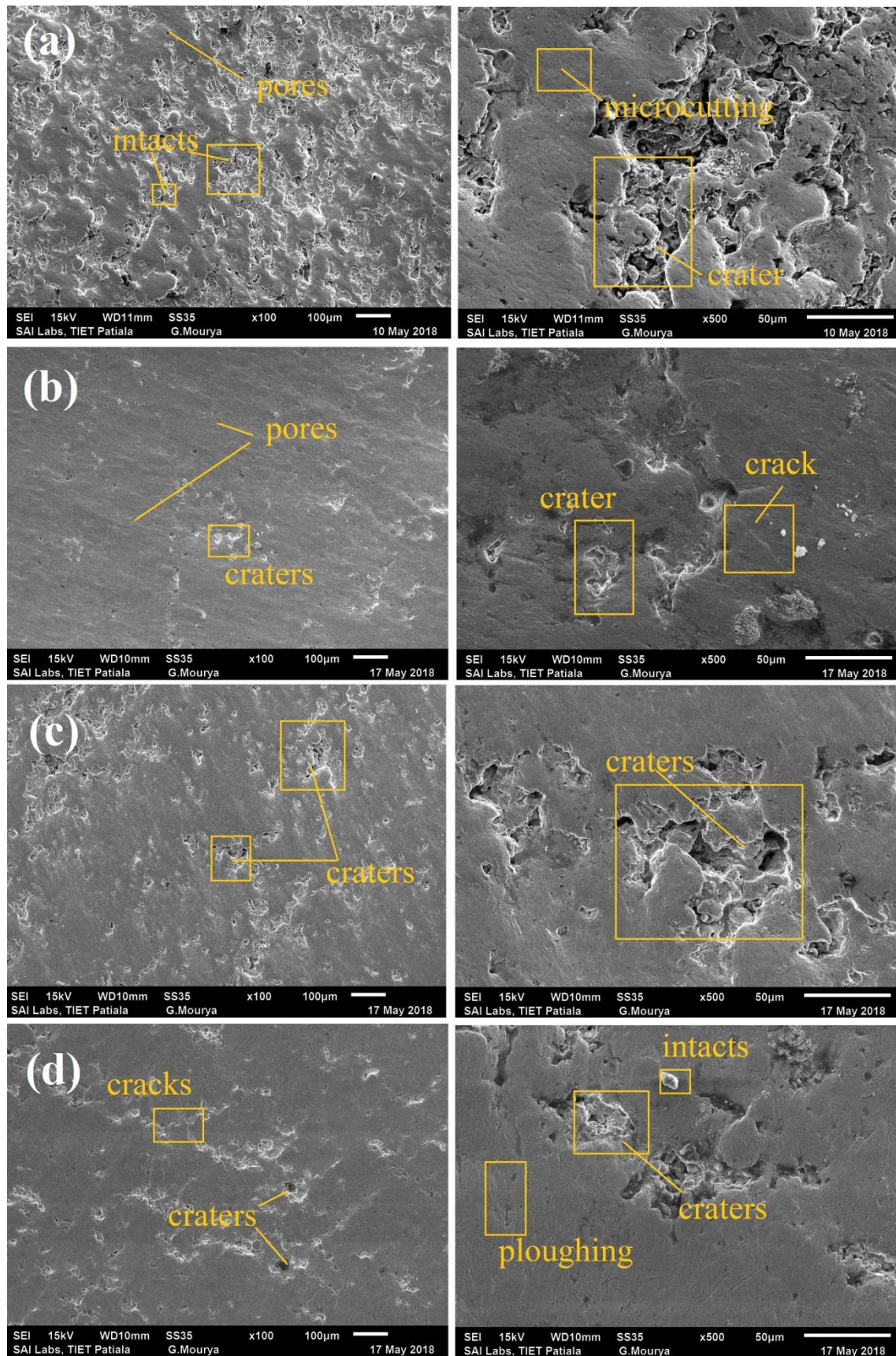


Figure 6.32. Erosion wear mechanism of Colmonoy-88 coating at impact angle of (a) 0°, (b) 30°, (c) 45°, and (d) 60°; for bottom ash slurry.

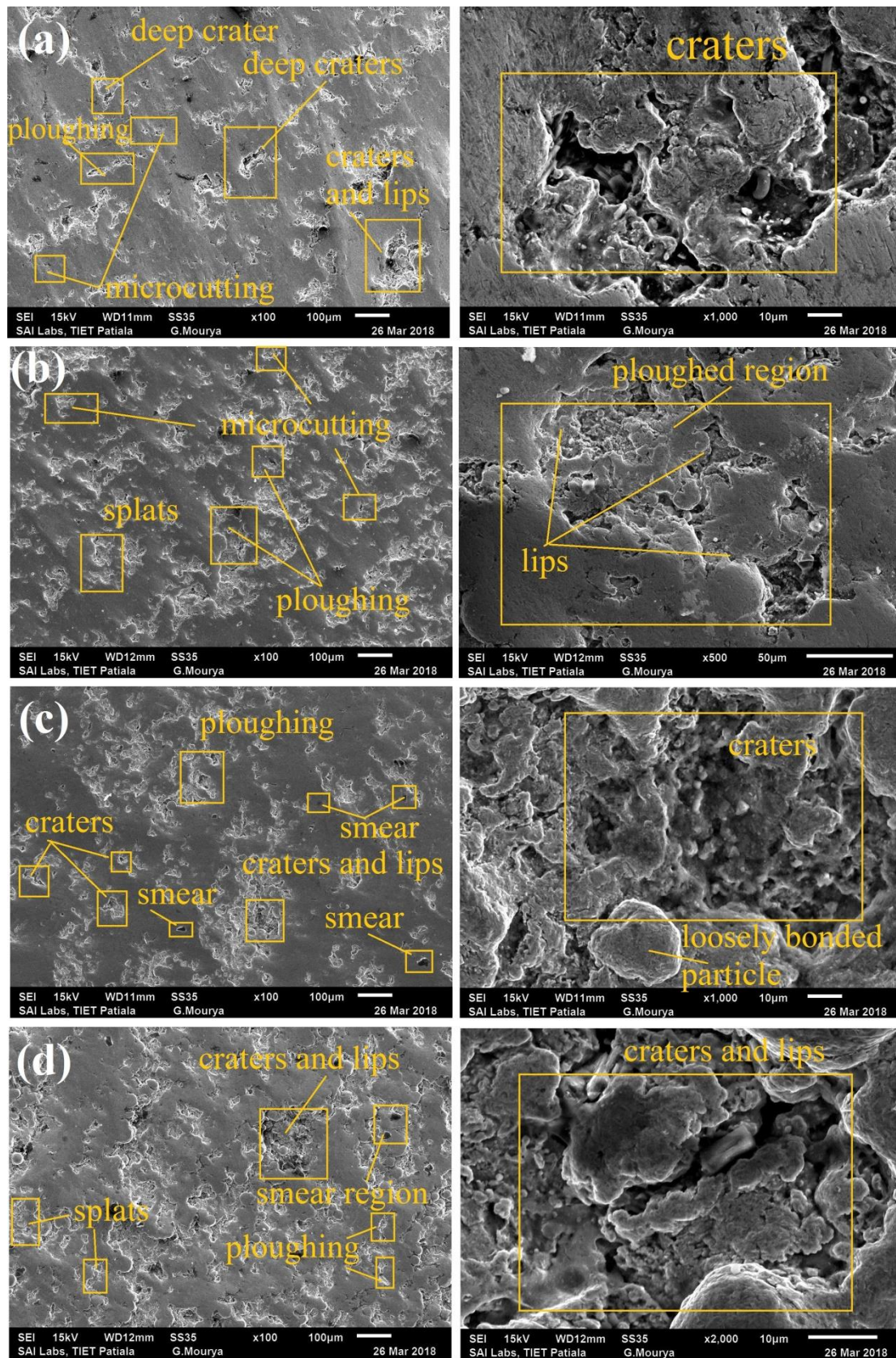


Figure 6.33. Erosion wear mechanism of Stellite-6 coating at impact angle of (a) 0°, (b) 30°, (c) 45°, and (d) 60°; for sand slurry.

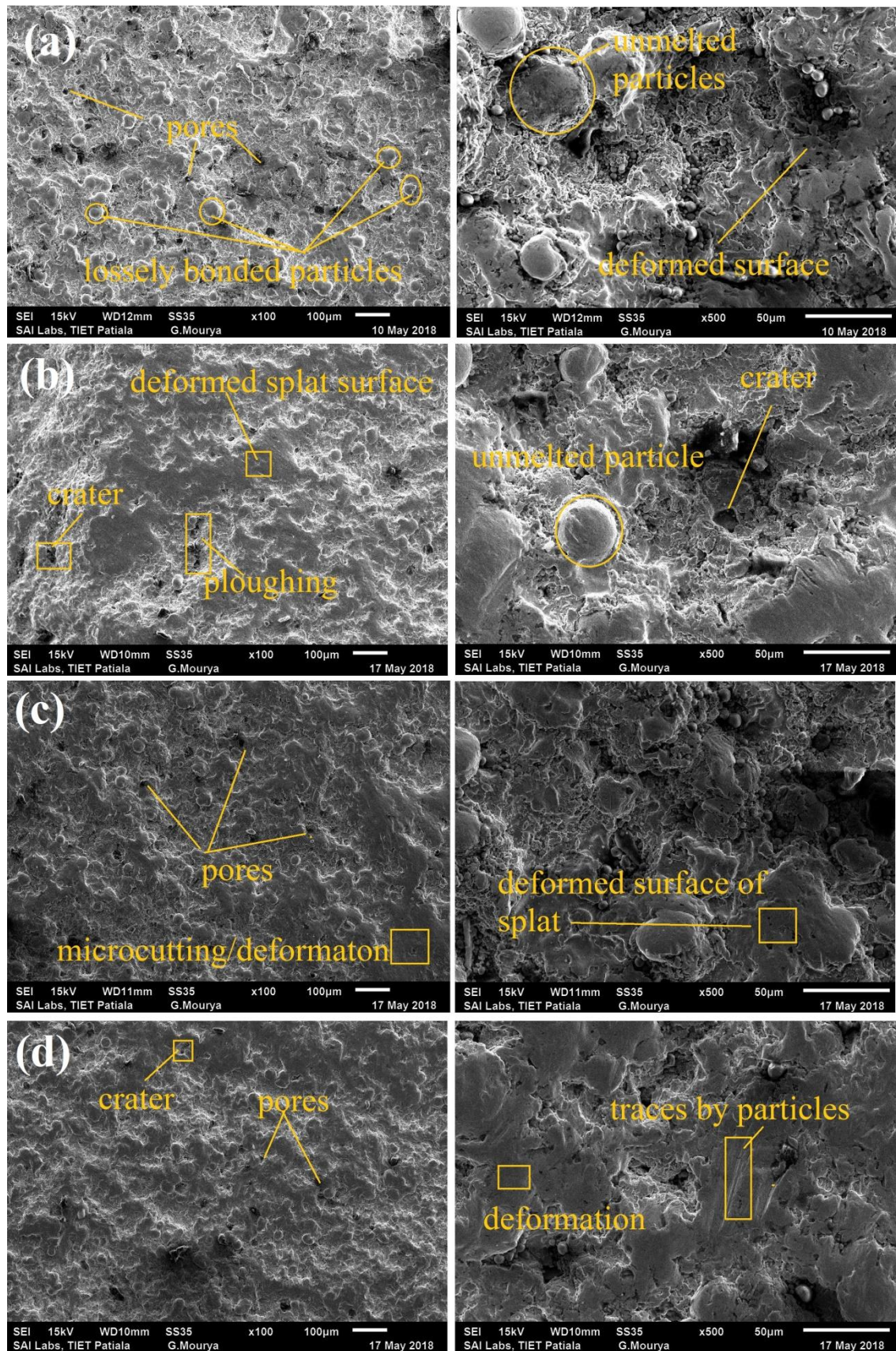


Figure 6.34. Erosion wear mechanism of Stellite-6 coating at impact angle of (a) 0°, (b) 30°, (c) 45°, and (d) 60°; for fly ash slurry.

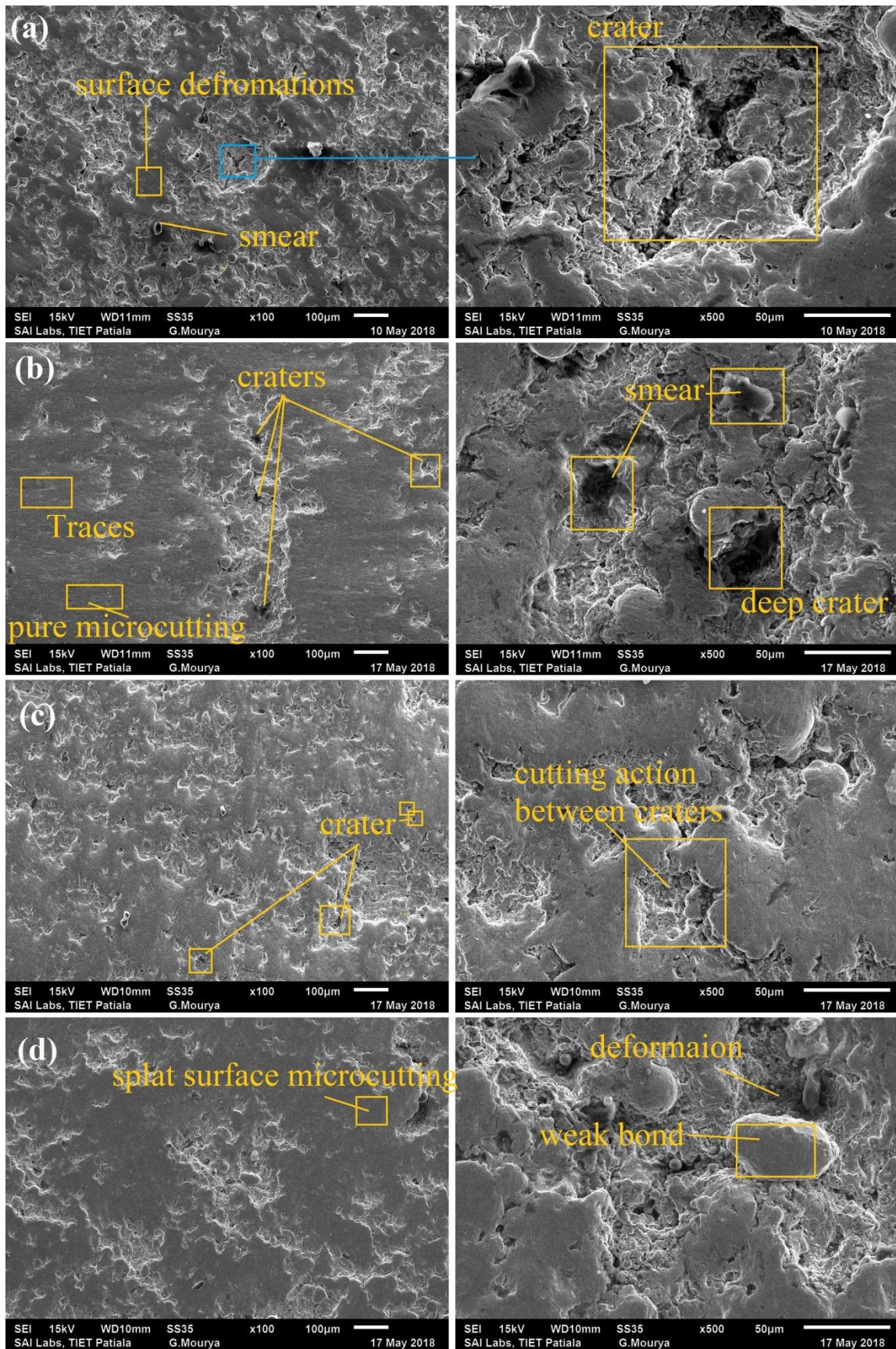


Figure 6.35. Erosion wear mechanism of Stellite-6 coating at impact angle of (a) 0°, (b) 30°, (c) 45°, and (d) 60°; for bottom ash slurry.

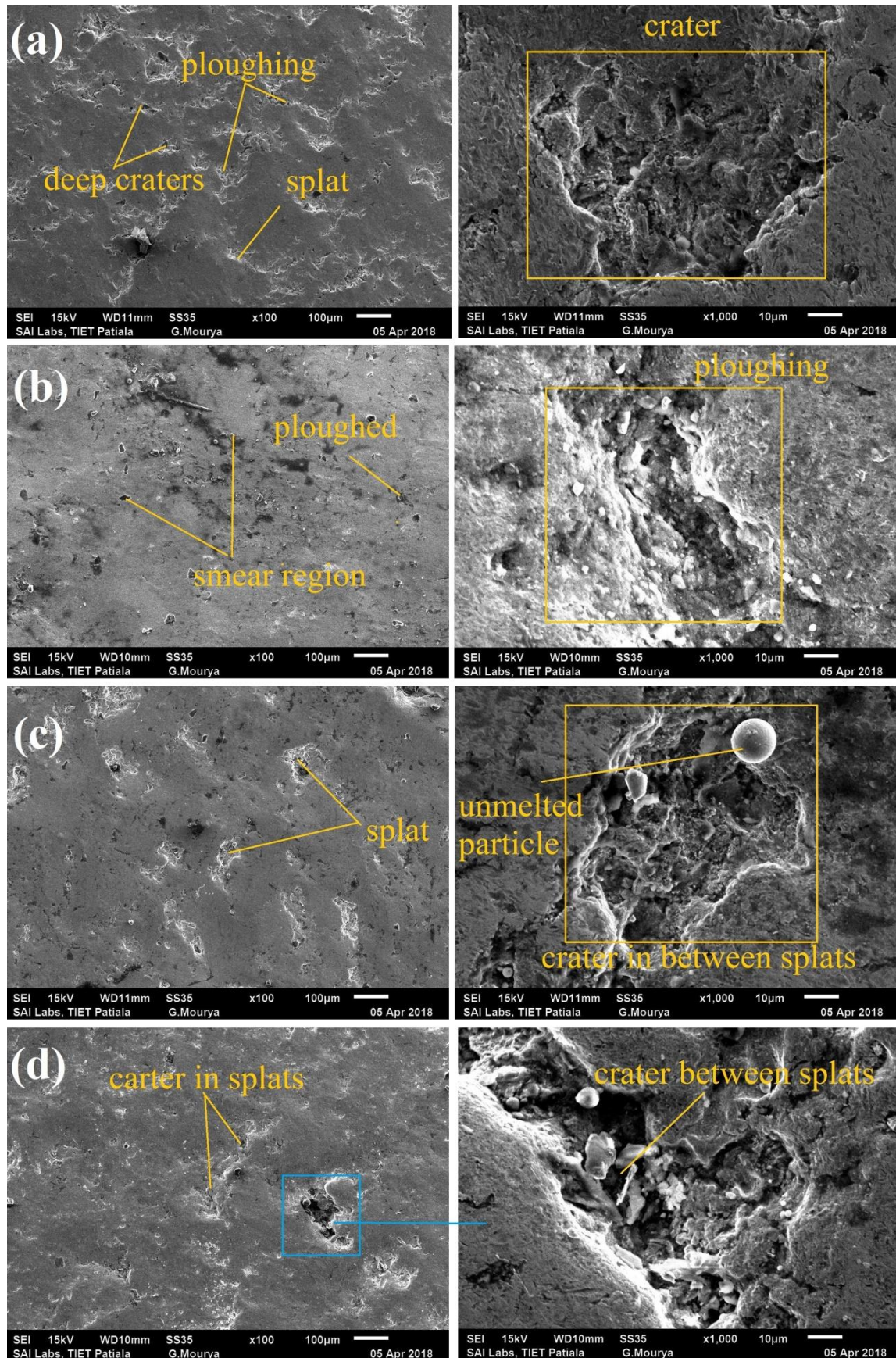


Figure 6.36. Erosion wear mechanism of Ni-20Cr₂O₃ coating at impact angle of (a) 0°, (b) 30°, (c) 45°, and (d) 60°; for sand slurry.

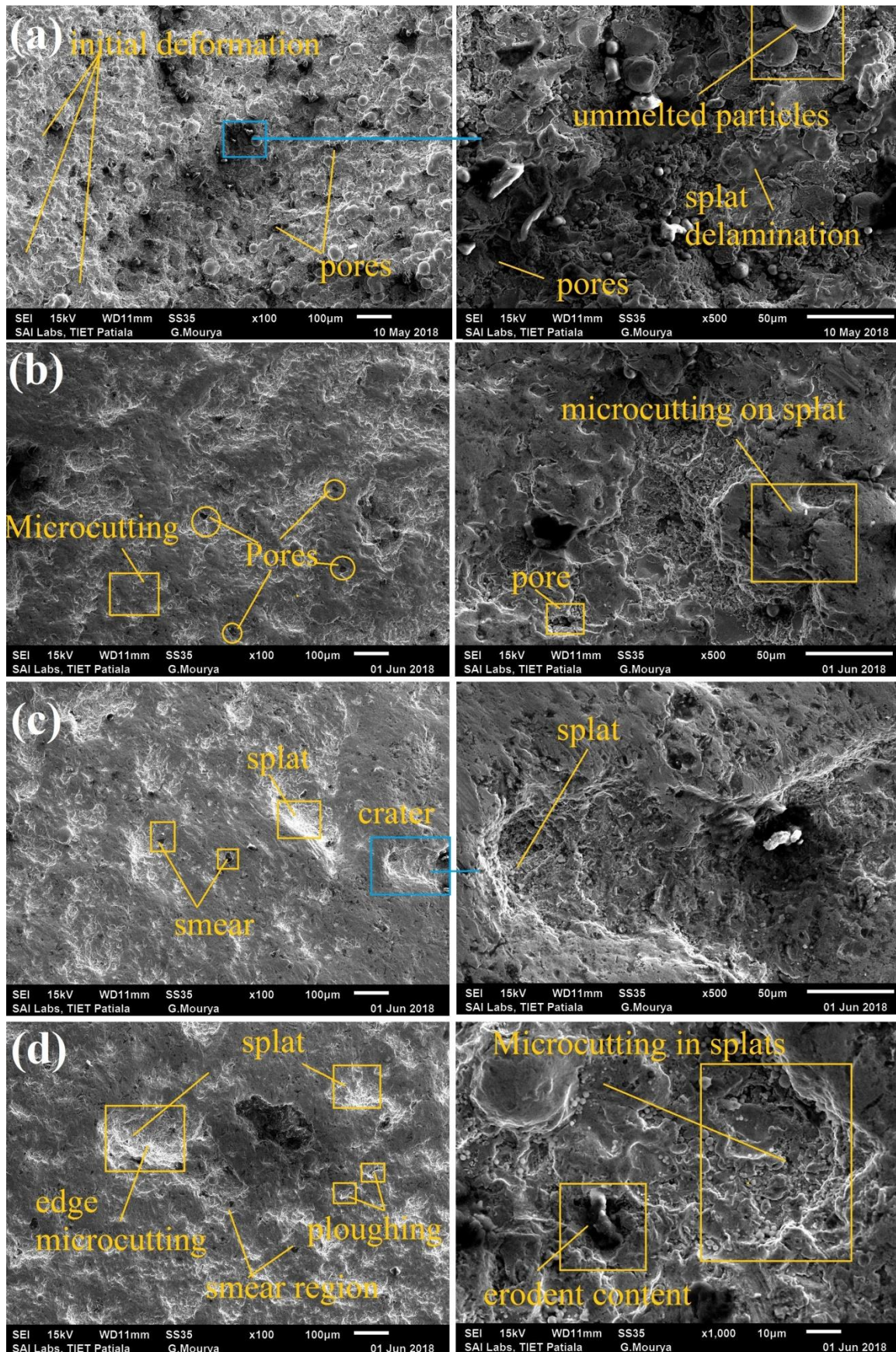


Figure 6.37. Erosion wear mechanism of Ni-20Cr₂O₃ coating at impact angle of (a) 0°, (b) 30°, (c) 45°, and (d) 60°; for fly ash slurry.

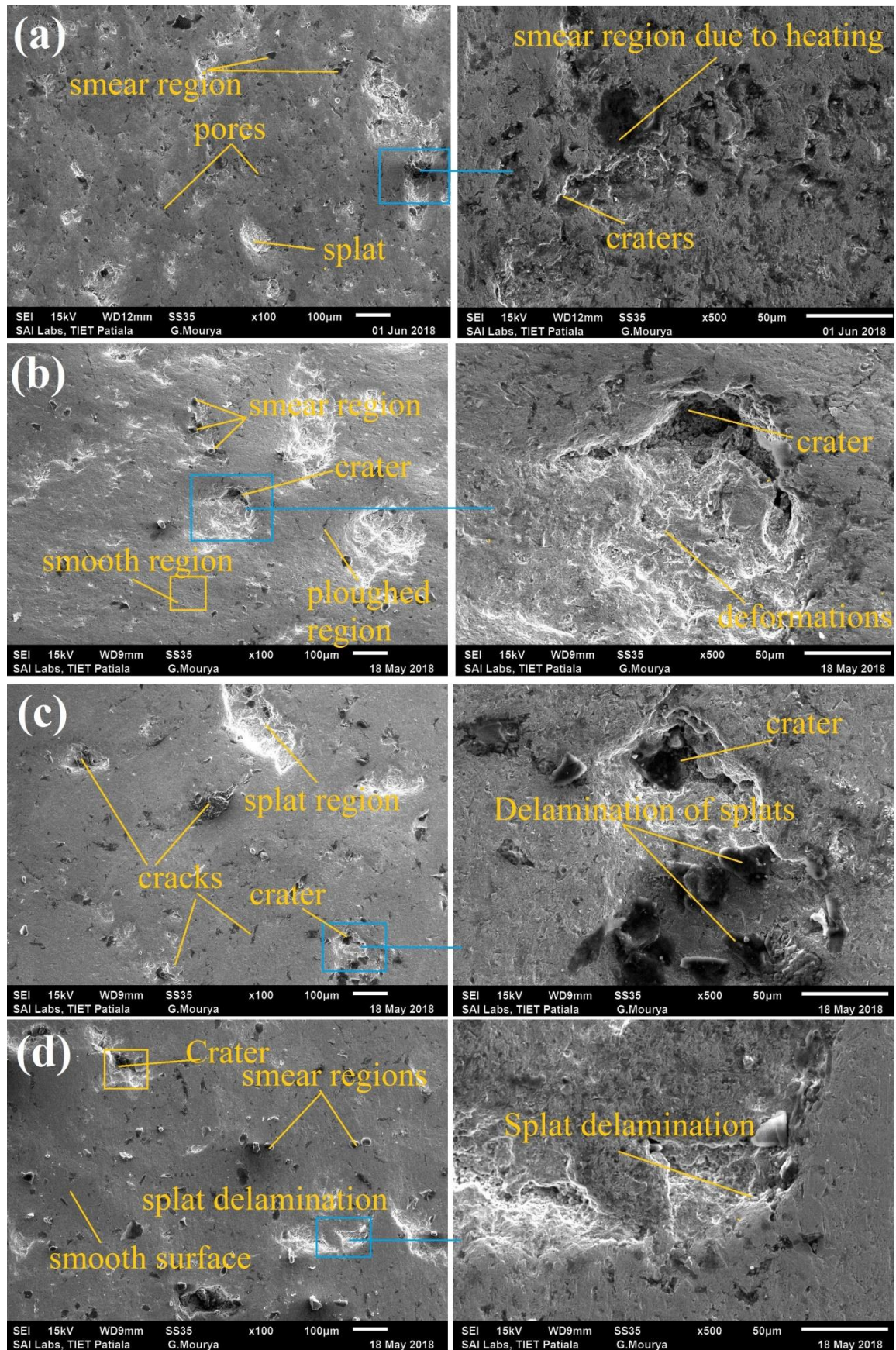


Figure 6.38. Erosion wear mechanism of Ni-20Cr₂O₃ coating at impact angle of (a) 0°, (b) 30°, (c) 45°, and (d) 60°; for bottom ash slurry.

6.5.3 Microstructure of eroded Ni-20Cr₂O₃ coatings

Erosion wear failure mechanisms that occurred on the surface of the Ni-20Cr₂O₃ coating by different slurries are shown in Figure 6.36-6.38. The eroded Ni-20Cr₂O₃ coating underwent to ploughing, microcutting and craters. In Figure 6.36(a), the commonly observed erosion wear mechanisms are ploughing, craters, ductile fractures. Microcutting was observed throughout at all impact angles whereas at high impact angle i.e. (60°), the ductile fractures were observed. The erosion wear mechanism was observed as ductile on the surface of Ni-20Cr₂O₃ coating.

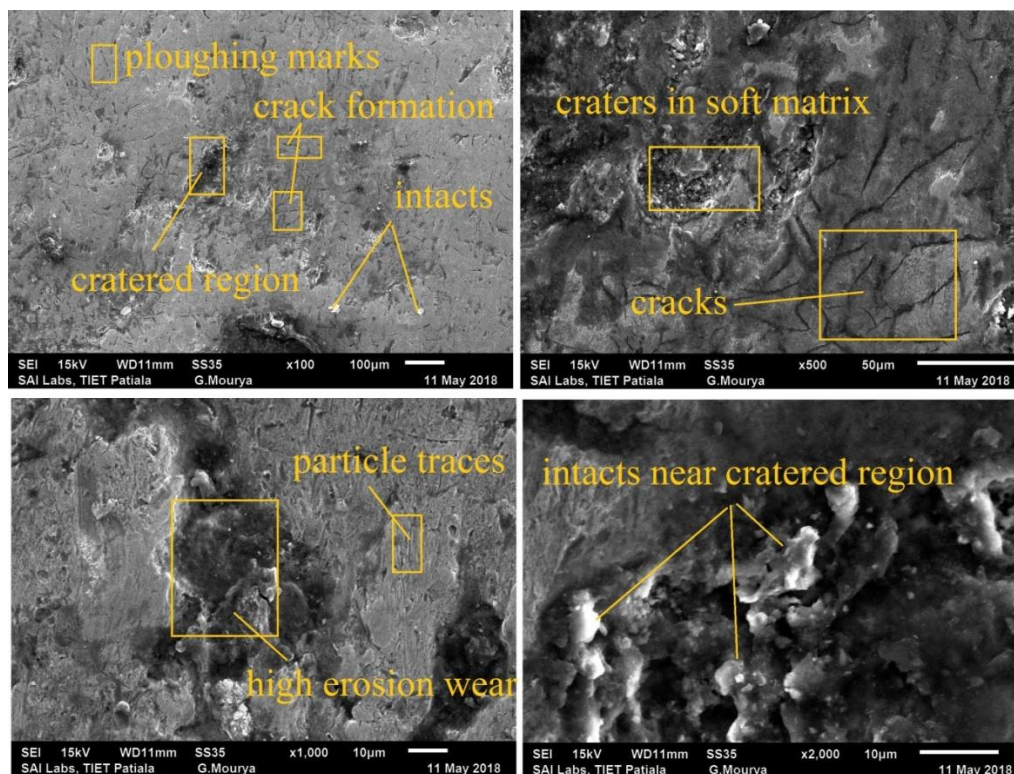


Figure 6.39. Erosion wear mechanism of Ni-20Al₂O₃ coating at impact angle of 0° for sand slurry.

6.5.4 Microstructure of eroded Ni-20Al₂O₃ coatings

The microstructure of erosion wear failure mechanisms occurred on the surface of the Ni-20Al₂O₃ coating is shown in Figure 6.39-6.41. Nickel is the brittle phase in Ni-20Al₂O₃ coating so, the obvious mechanism was the fractures (Tadeusz and Szala, 2013; Szala et al. 2014). The eroded Ni-20Al₂O₃ coating underwent to ploughing, intact regions, brittle carbide fractures, and carbide pull-outs. The eroded surface SEM micrographs of Ni-20Al₂O₃ coating with sand slurry are shown in Figure 6.41.

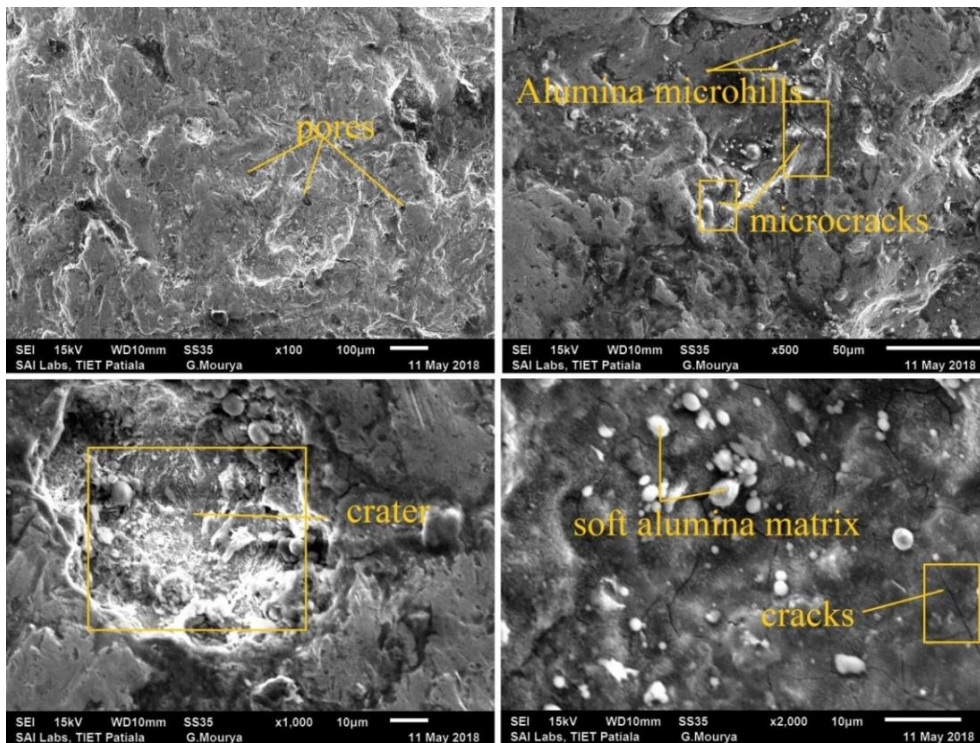


Figure 6.40. Erosion wear mechanism of Ni-20Al₂O₃ coating at impact angle of 0° for fly ash slurry.

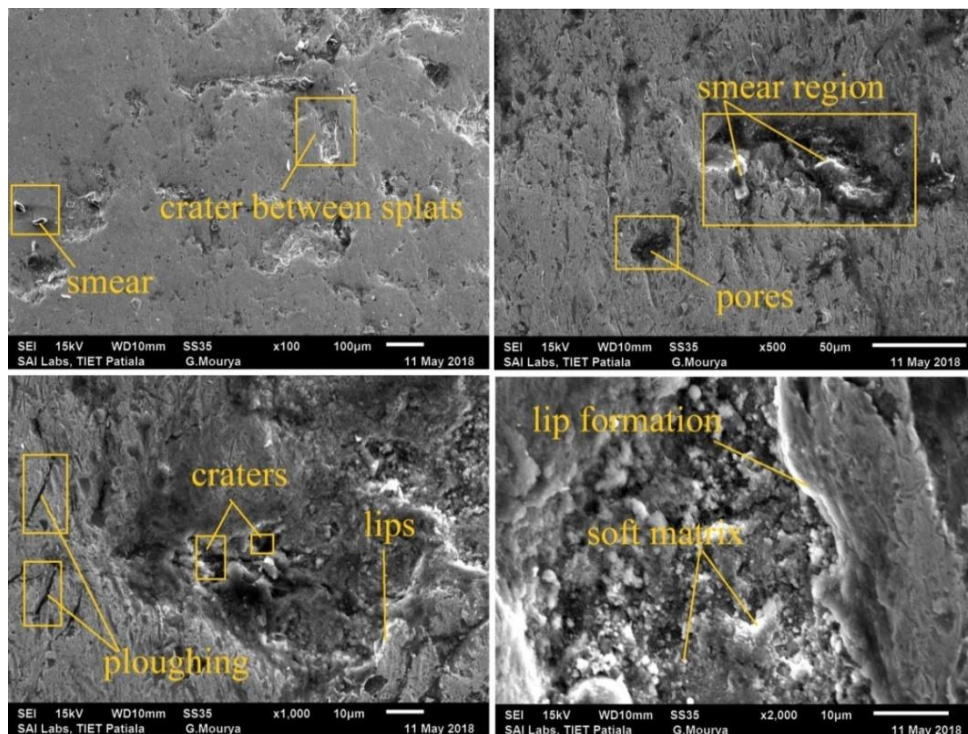


Figure 6.41. Erosion wear mechanism of Ni-20Al₂O₃ coating at impact angle of 0° for bottom ash slurry.

It was notified that microhills present on the Ni-20Al₂O₃ coating at different locations. Simultaneously, the loosely bonded cremate grains from the surface of Ni-20Al₂O₃ coating by impact of erodent particles. Furthermore, no crack or splat debonding was observed on the surface which indicates the ductile behavior of the coating. Alumina has high microhardness which contribute in reduction of erosion wear process (Ganaraja et al. 2013; Stojanović and Ivanović, 2015).

6.5.5 Microstructure of eroded Al-20TiO₂ coatings

The microstructure of erosion wear failure mechanisms occurred on the surface of the Al-20TiO₂ coating by different slurries is shown in Figure 6.42-6.44. Aluminium is ductile in nature so it undergoes to microcutting action (Prashad et al. 2001; Stojanović and Ivanović, 2015). The eroded Al-20TiO₂ coating underwent to lip formation, ploughing and microcutting.

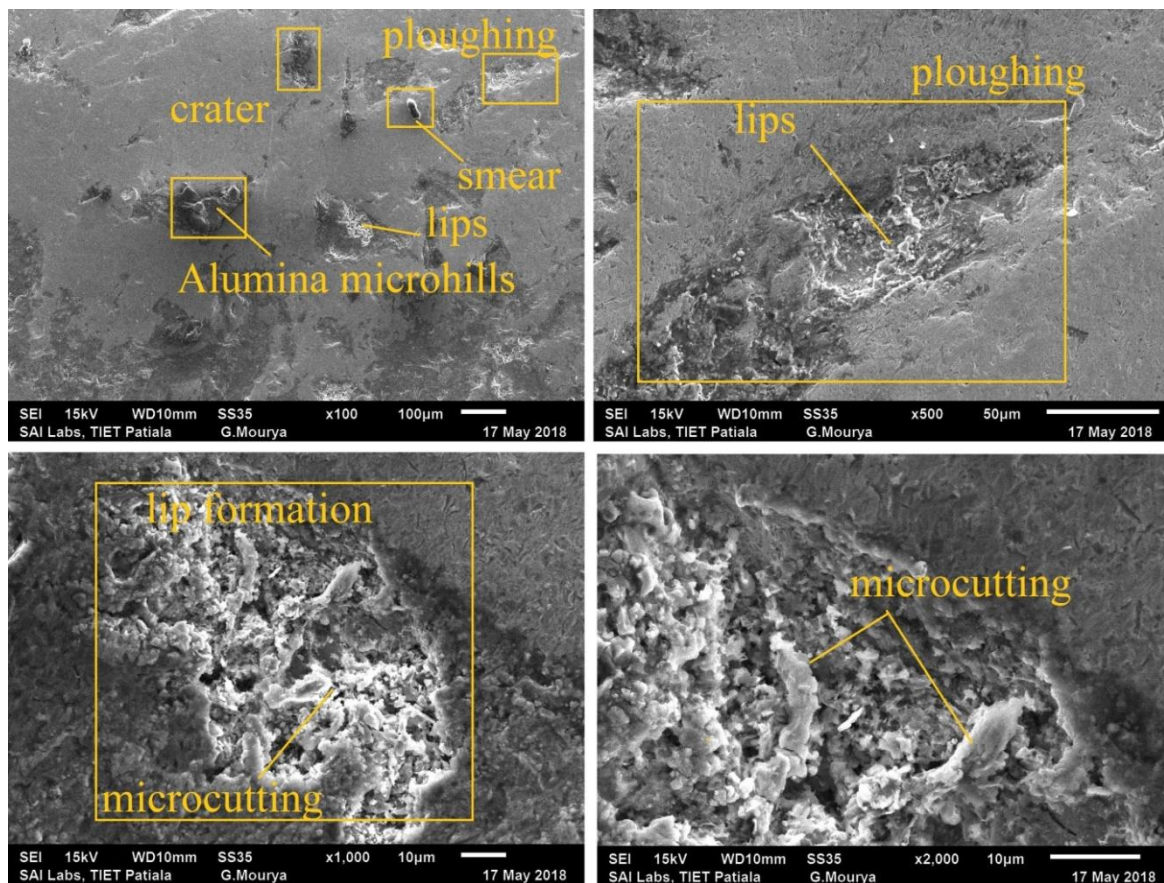


Figure 6.42. Erosion wear mechanism of Al-20TiO₂ coating at impact angle of 0° for sand slurry.

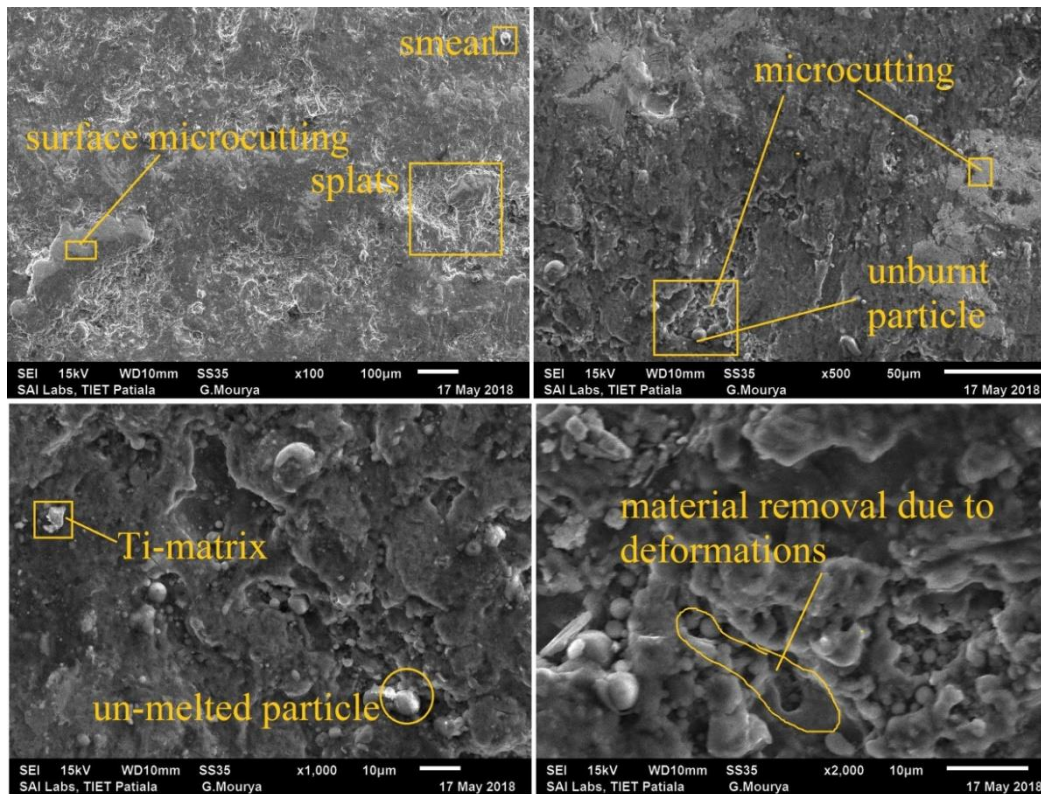


Figure 6.43. Erosion wear mechanism of Al-20TiO₂ coating at impact angle of 0° for fly ash slurry.

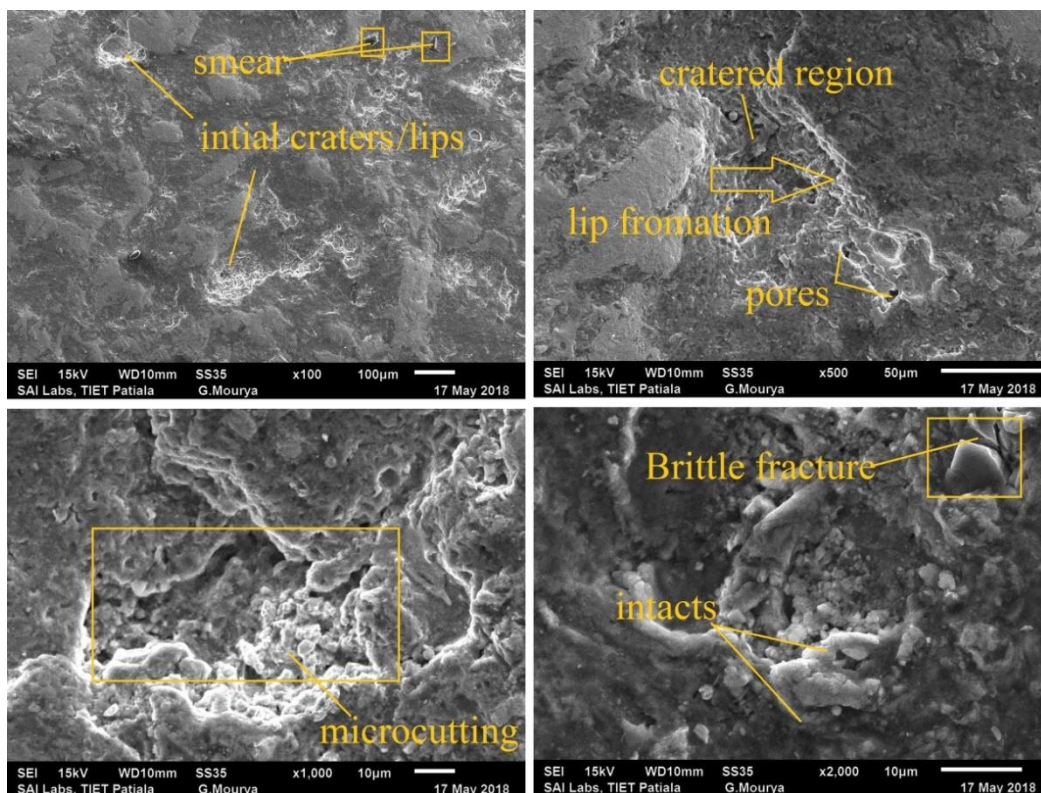


Figure 6.44. Erosion wear mechanism of Al-20TiO₂ coating at impact angle of 0° for bottom ash slurry.

6.6 GENERAL OBSERVATIONS FROM EROSION WEAR RESULTS

The erosion wear patterns were indifferent in physical appearance for every concentration with time duration. Figure 6.45(a) shows the schematic diagram wear phenomenon of eroded surfaces at leading and tailing surfaces. The erosion wear occurred at the leading edge was comparatively higher as compared to tailing edge. Erosion wear patterns observed on the specimen indicates that the surfaces directly exposed to slurry particles erode more than the surface following the leading surfaces. The phenomenon of erosion wear of the specimen in pot tester changes while moving from central vertical-axis towards edge along longitudinal-axis. As the radius of workpiece increases the relative erosion wear also increases, as shown in Figure 6.45(b).

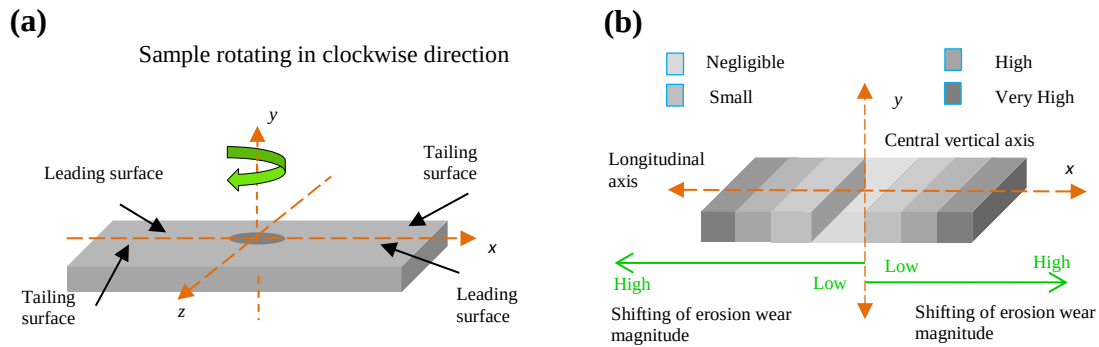


Figure 6.45. Erosion wear phenomenon (a) at leading & tailing surfaces, and (b) along the transverse length of workpiece.

6.7 REMARKS

- The order of roughness is as follows: Ni-20Cr₂O₃ > Colmonoy-88 > Stellite-6 > Ni-20Al₂O₃ > Al-20TiO₂.
- The order of microhardness is as follows: Ni-20Cr₂O₃ > Colmonoy-88 > Stellite-6 > Ni-20Al₂O₃ > Al-20TiO₂
- The average surface microhardness of Stellite-6, Colmonoy-88, Ni-20Cr₂O₃, Ni-20Al₂O₃ and Al-20TiO₂ deposited SS-316L is 449.079, 607.846, 821.014, 315.521 and 291.077 H.V. respectively.
- The order of erosion wear with variation in solid concentration, time duration and velocity is as follows: Colmonoy-88 < Stellite-6 < Ni-20Cr₂O₃ < Ni-20Al₂O₃ < Al-20TiO₂.

- Erosion wear of different coatings was decreased with increase in CF value of erodent particles. The exponent of CF value is calculated in the present study that holds good agreement with statement reported by Walker and Humbe (2015).
- Maximum erosion is observed at 30° impact angle arrangement for Stellite-6 and Ni- $20Cr_2O_3$ coatings whereas at 60° impact angle for Colmonoy-88, Ni- $20Al_2O_3$ and Al- $20TiO_2$ coatings. Stellite-6 and Ni- $20Cr_2O_3$ coating shows the ductile erosion wear whereas Colmonoy-88, Ni- $20Al_2O_3$ and Al- $20TiO_2$ shows the semi-brittle erosion wear behavior.

CHAPTER 7

SIMULATION OF EROSION WEAR OF THERMALLY SPRAYED COATINGS

CHAPTER 7

SIMULATION OF EROSION WEAR OF THERMALLY SPRAYED COATINGS

7.1 INTRODUCTION TO ARTIFICIAL INTELLIGENCE

Erosion wear process is a complex phenomenon which involves a large number process parameters and material/erodent properties. In previous chapters, the erosion wear different pumping materials and coatings were investigated experimentally. In this chapter, the artificial intelligence is utilized to predict the erosion wear. Artificial Neural Network (ANN) technique is a prototype model of network made by biological neurons and it has been used in variety of disciplines to solve different problems. This technique was developed on the basis of biological neurons which are used to simulate the learning, clustering and reasoning of problem. An artificial network requires training before prediction of results for a specific problem. An artificial network can be well-trained as well as over-trained. A network generally becomes over-trained while it has to predict the few results from a quantitative input data. A well trained network can be used to provide pattern classification/association or predictive performance. From literature, it is clear that the erosion wear is a complex phenomenon which is lacking in terms of providing a correlation. So in this case, ANN can be an alternate to provide the general solution of erosion wear problems.

7.2 NEURAL NETWORK MODEL

As mentioned earlier, Neural networks are the massively parallel distributed processing systems which offer the learning based prediction instead of detailed information based on knowledge about the system or process (Mihalakakou et al. 2000; Stojanovic et al. 2016). In present study, standard multilayer feedforward hierarchical neural network designed in MATLAB 16.0 was used to predict the erosion wear. A standard multilayer feedforward hierarchical neural network designed in MATLAB 16.0 was used to predict the erosion wear. Figure 7.1 shows three-layer neural network which consist of an input, output and hidden layer. Input layer consists of five input neurons namely speed, concentration, time, impact angle and coating microhardness whereas output layer represents the predicted value of erosion wear. Each of the input parameters represents the characteristic of one neuron in input layer of ANN structure.

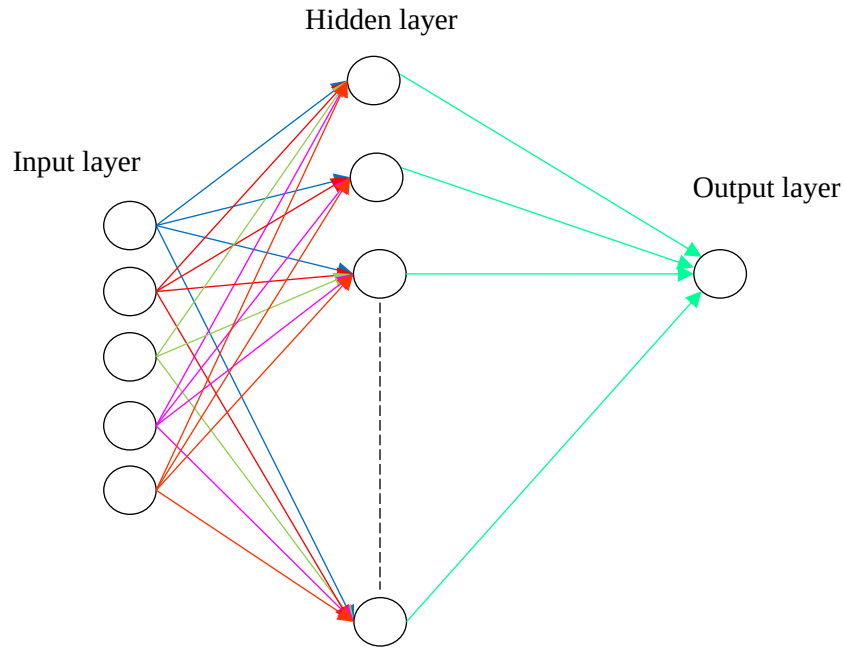


Figure 7.1. 3-layer model of neural network.

Table 7.1: Training input parameters of ANN structure for prediction of erosion wear by sand slurry

S. No.	Training input parameters	Symbol	Values
1	Error tolerance		0.005
2	Learning rate	β	0.002
3	Momentum parameter	α	0.002
4	Noise factor	NF	0.001
5	No. of epochs		1,00,00,000
6	Slope parameter	ξ	0.6
7	No. of hidden layer neurons	H	20
8	No. of input layer neurons	I	5
9	No. of output layer neurons	O	1
10	Adaption learning function		LEARNGDM
11	Transfer function		TANSIG
12	Training function		TrainLM
13	Performance function		MSE

7.3 TRAINING OF NEURAL NETWORK MODEL

Three different ANN structures were developed for same input parameters for predication of erosion wear due to three different slurries namely sand, fly ash and bottom ash. The number of neurons varies in the hidden layer for each of the ANN structure. Each ANN structure was tested at different input parameters of training mentioned in Table 7.1 and 7.2.

Table 7.2: Training input parameters of ANN structure for prediction of erosion wear by fly and bottom ash slurry

S. No.	Training input parameters	Symbol	Values
1	Error tolerance		0.0055
2	Learning rate	β	0.002
3	Momentum parameter	α	0.002
4	Noise factor	NF	0.001
5	No. of epochs		1,00,00,000
6	Slope parameter	ϵ	0.6
7	No. of hidden layer neurons	H	20
8	No. of input layer neurons	I	5
9	No. of output layer neurons	O	1
10	Adaption learning function		LEARNGDM
11	Transfer function		TANSIG
12	Training function		TrainLM
13	Performance function		MSE

7.3.1 Training model

Neural network was trained with the help of Levenberg-Marquardt algorithms which provides fastest convergence (Hagan and Menhaj, 1994). Nguyen-Widrow algorithm is used to generate initial weights and values for layer. Back propagation learning rule was applied to minimize the error which is given as:

$$\Delta W_{ij} = \eta \frac{\partial E}{\partial w_{ij}} \quad (7.1)$$

Where, η is the learning rate parameter, $\frac{\partial E}{\partial W_{ij}}$ is the error gradient with reference to the weight W_{ij} . Term ΔW_{ij} represents the weight update of the link connecting the i^{th} and j^{th} neuron of the two neighboring layers.

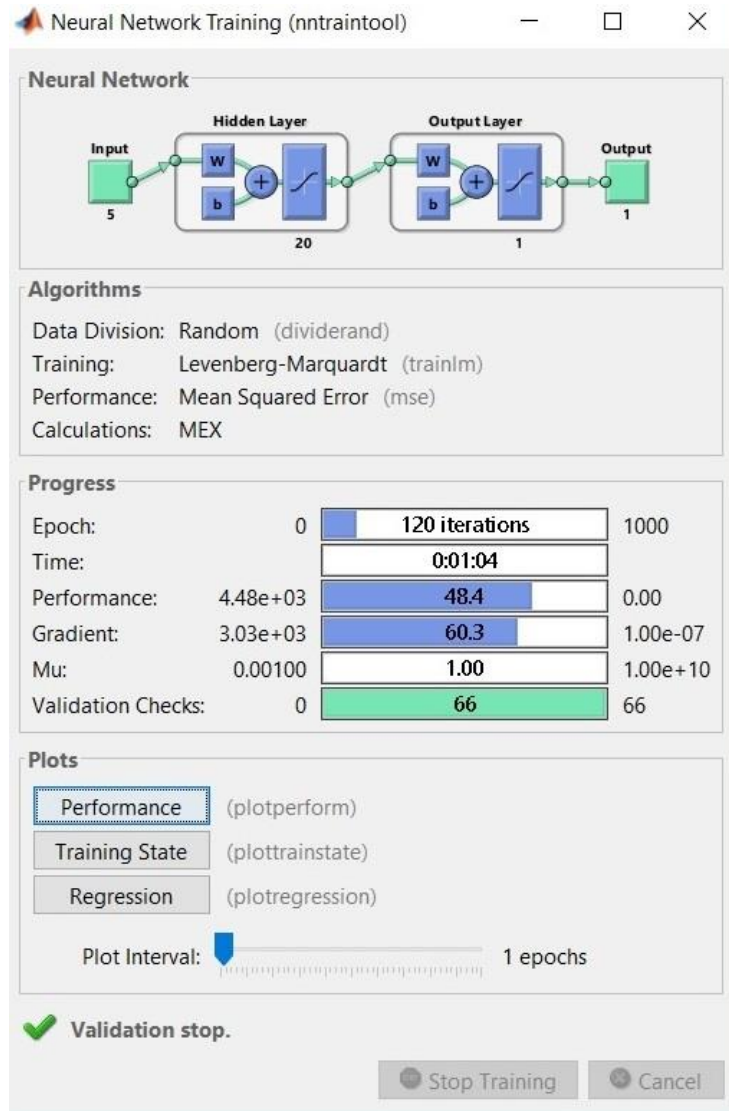


Figure 7.2. Training parameters used in erosion wear prediction for sand slurry.

7.3.2 Training parameters

The training parameters used in erosion wear prediction for different slurries are shown in Figure 7.2-7.4. The training and testing functions were normalized in range 0.1-0.9 by using the following equation:

$$y = 0.1 + 0.8 \left(\frac{x - x_{min}}{x_{max} - x_{min}} \right) \quad (7.2)$$

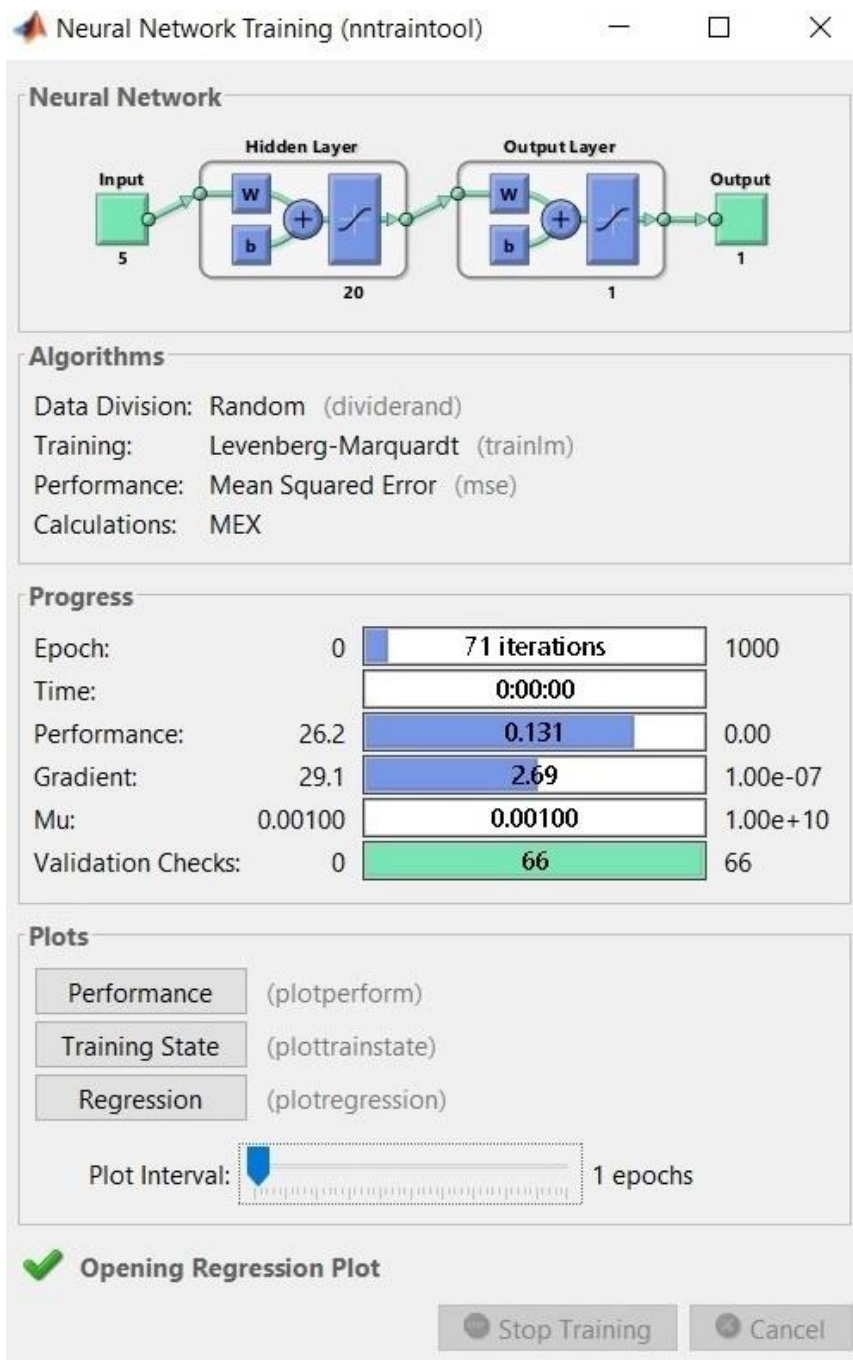


Figure 7.3. Training parameters used in erosion wear prediction for fly ash slurry.

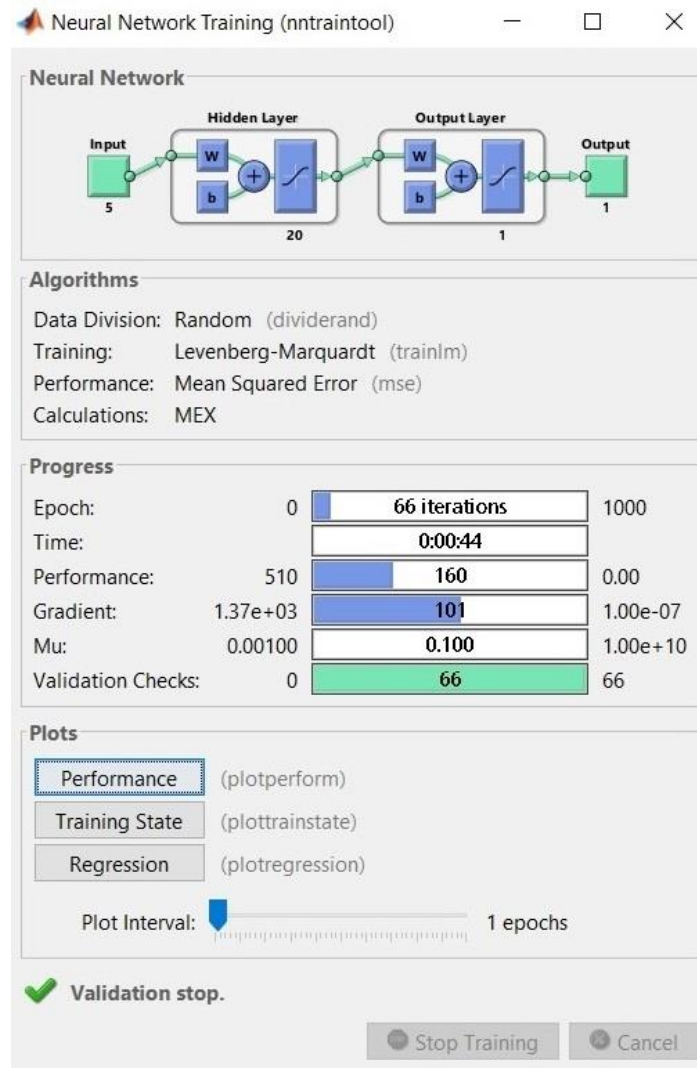


Figure 7.4. Training parameters used in erosion wear prediction for bottom ash slurry.

7.4 TESTING AND VALIDATION OF NEURAL NETWORK MODEL

Mean square error (MSE) was used for evaluating the performance between experimental and predicted value. Figure 7.5-7.7 show the network performance during the training, testing and validation. The hidden layers neurons were varied as 10, 15, 20, and 25 in trails. The best results were achieved 20 neurons of hidden layer which has been represented in present work. For this analysis, total of 20 neurons (hidden layer) were taken for training of network. 75% data was used for training, 12.5% data was used for testing and 12.5% data was used for validation. It can be observed that the value of error lie in range 0-5% it indicates the validity of neural network computations. However, the errors can still be minimized by using more data for training and less data for testing and validations. To avoid the case of over-trained network the 75% data is sufficient to train the network. On the other hand, a well-trained network provides an erosion wear investigation by permitting the quantitative effect of

different input parameters. ANN prediction for any parameter does not lie in a close range. It could be beyond the experimental values which represents the large parametric space in ANN prediction.

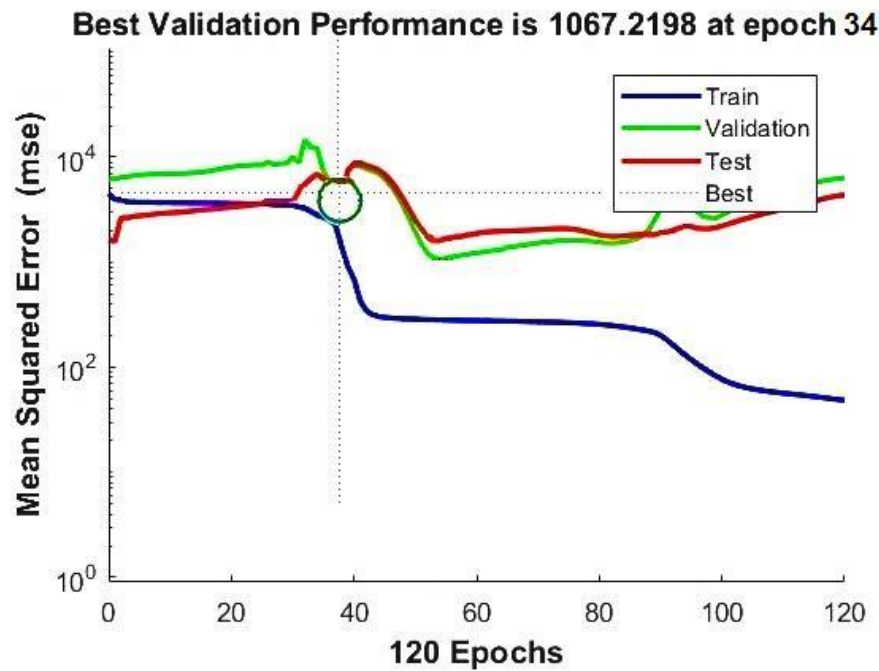


Figure 7.5. Performance of neural network at time of training-testing-validation process for simulation of erosion wear by sand slurry.

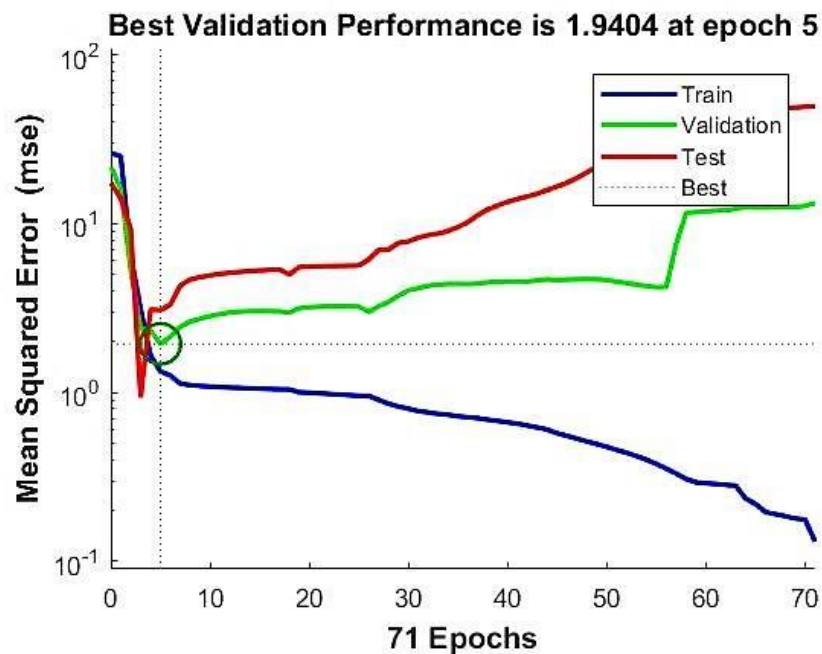


Figure 7.6. Performance of neural network at time of training-testing-validation process for simulation of erosion wear by fly ash slurry.

In present investigation, the parameters are varied in range as mentioned in experimentation. From Figure 7.5, the neural network was found to be zero error trained in 34 epochs for the ANN structure used for prediction of erosion wear by sand slurry. The neural network structure designed for erosion wear by fly ash slurry shows zero error 5 epochs, as shown in Figure 7.6. However, the neural network structure designed for erosion wear by bottom ash slurry shows zero error 31 epochs.

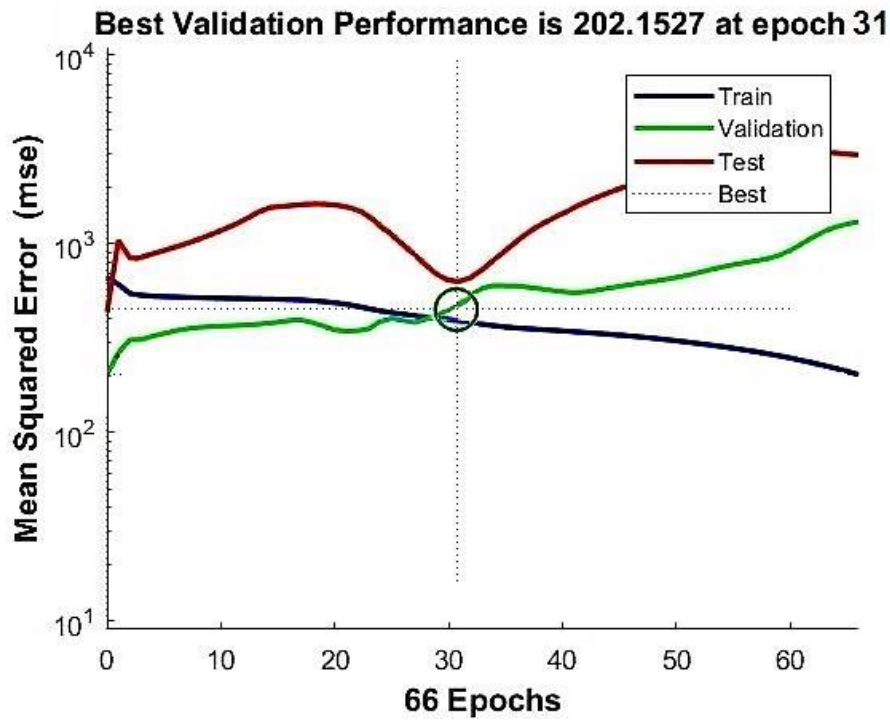


Figure 7.7. Performance of neural network at time of training-testing-validation process for simulation of erosion wear by bottom ash slurry.

7.5 REGRESSION ANALYSIS

After the training process, the validation of network step was followed for plotting the regression values for training, testing, validation and overall performance. Regression plots of erosion wear predicted for sand slurry by using ANN model are shown in Figure 7.8. Dashed line represents the targets which discriminate the perfect result and outputs. Colored solid lines represent the linear regression fitting line which discriminates between outputs and targets. From Figure 7.8, the value of regression coefficient (R^2) for training, testing, validation and performance of ANN model designed for sand slurry was found to be best fit and are 0.95656, 0.99536, 0.97534 and 0.96792 respectively. The value of regression coefficient (R^2) was found close to 1 which represents pure linear relationship between

outputs and targets. The value of regression coefficient (R^2) for training, testing, validation and performance of ANN model designed for fly ash slurry was found as 0.97123, 0.98451, 0.9638 and 0.98233 respectively, as shown in Figure 7.9. Similarly, the ANN model designed for bottom ash slurry shows the values of regression coefficient (R^2) as 0.95823, 0.96275, 0.95181 and 0.96706 respectively for training, testing, validation and performance (shown in Figure 7.10).

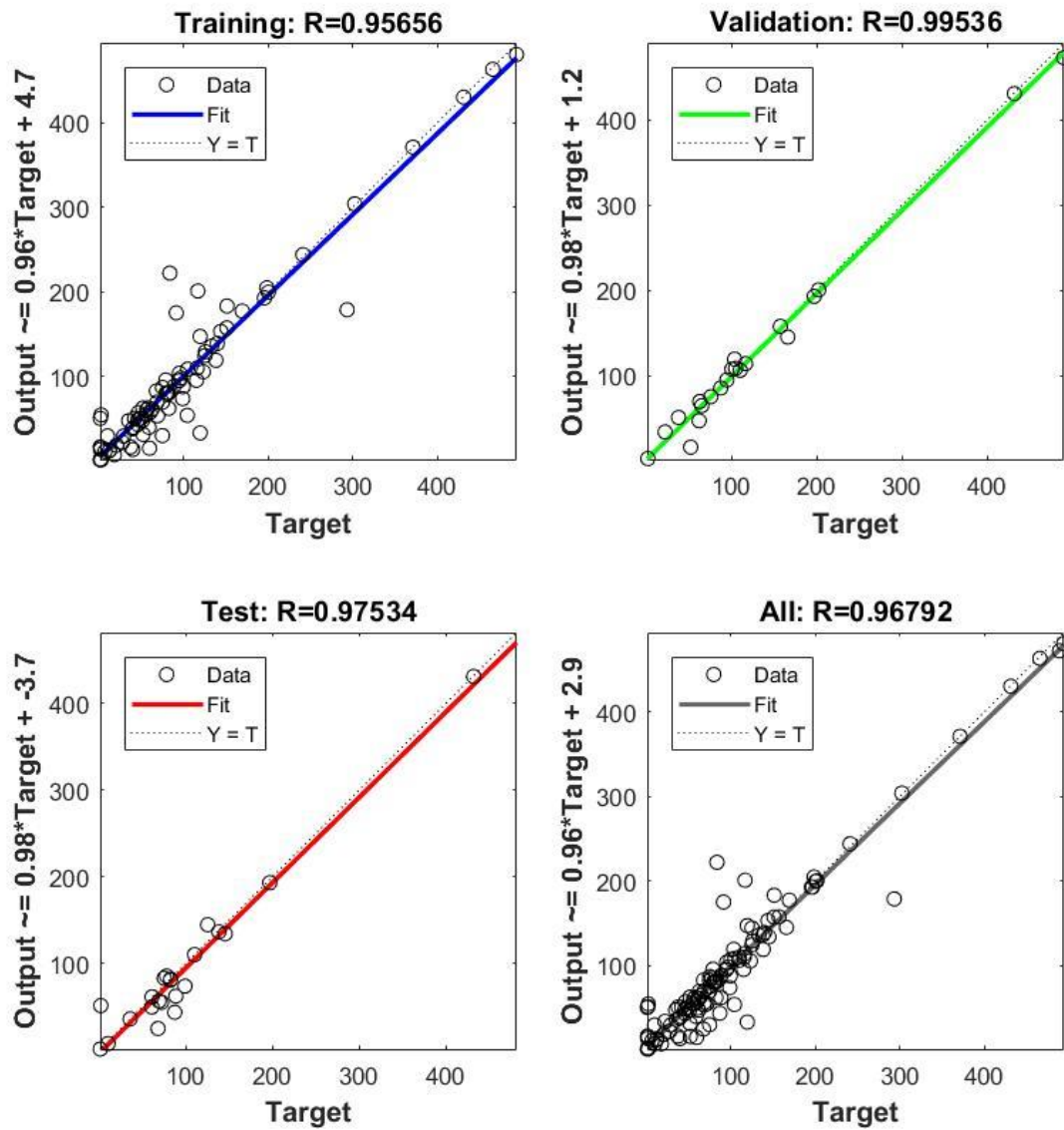


Figure 7.8. Regression plots of ANN predicted erosion wear model for sand slurry.

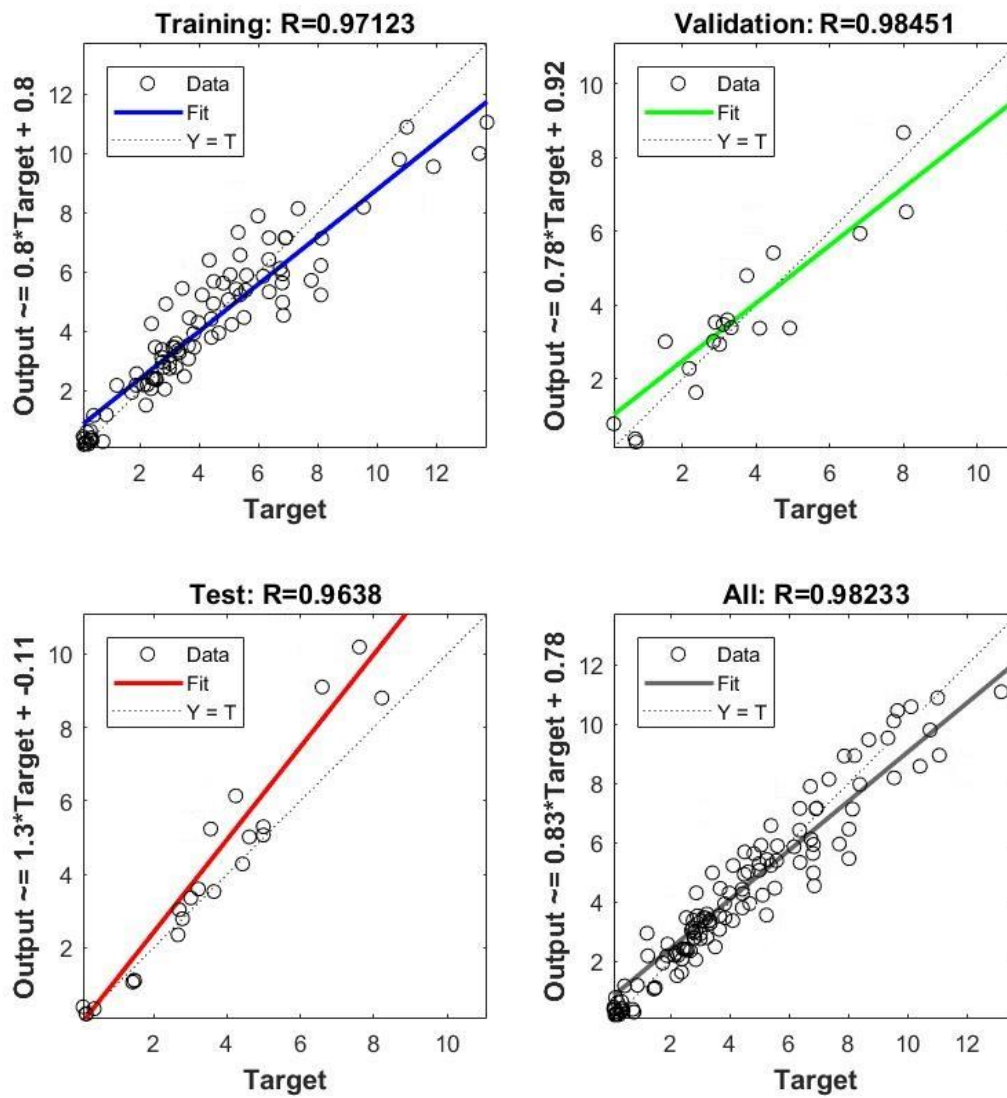


Figure 7.9. Regression plots of ANN predicted erosion wear model for fly ash slurry.

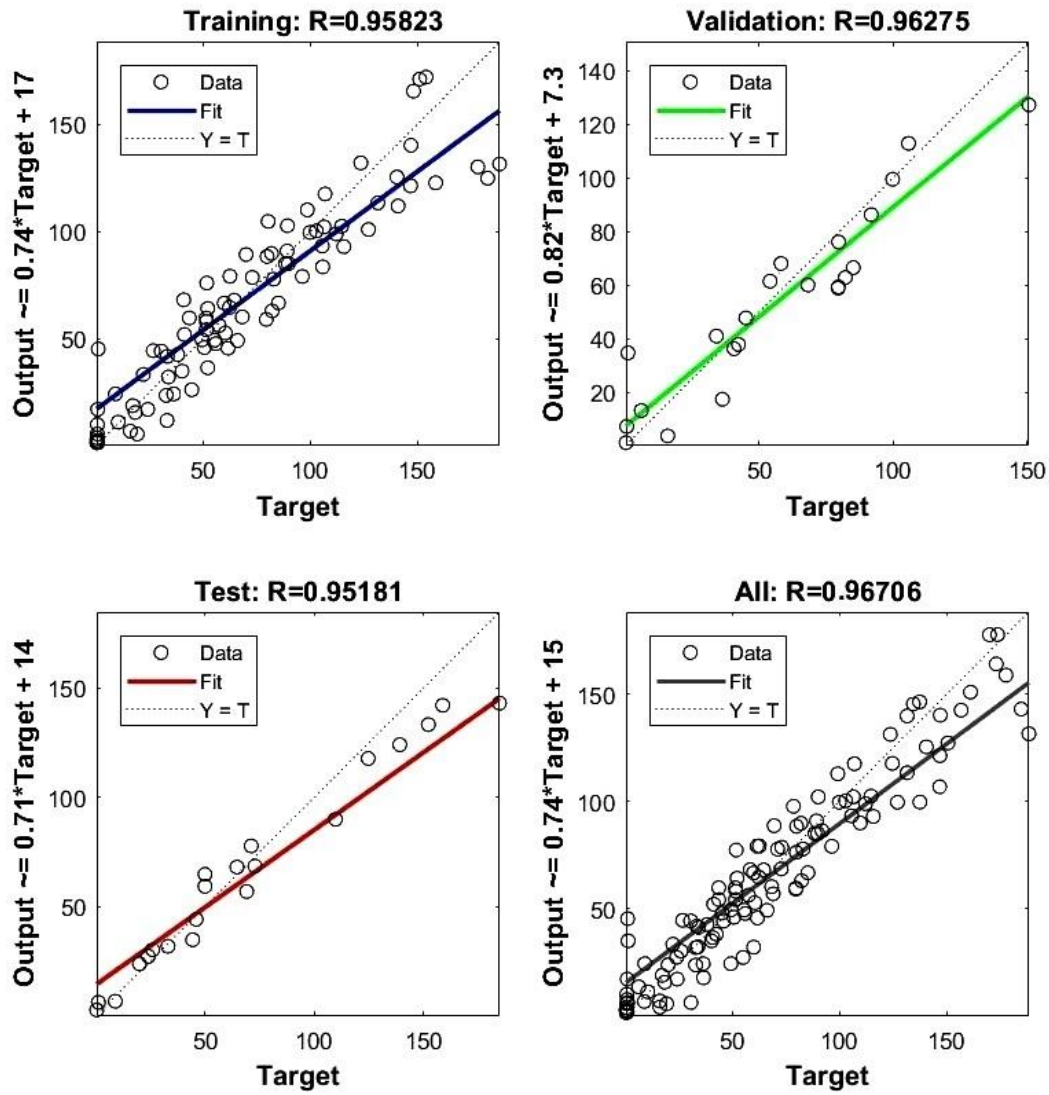


Figure 7.10. Regression plots of ANN predicted erosion wear model for bottom ash slurry.

7.6 ANALYSIS OF EROSION WEAR MODEL

Erosion wear predicted from ANN model is mentioned in Figure 7.11. It was found that ANN model designed for sand slurry shows $\pm 4.87\%$ deviation from the experimental data. However, the percentage error between experimental and ANN predicted erosion wear was found as 4.27 and 4.98% respectively for fly ash and bottom ash slurry which indicates the close agreement between neural network and experimental results.

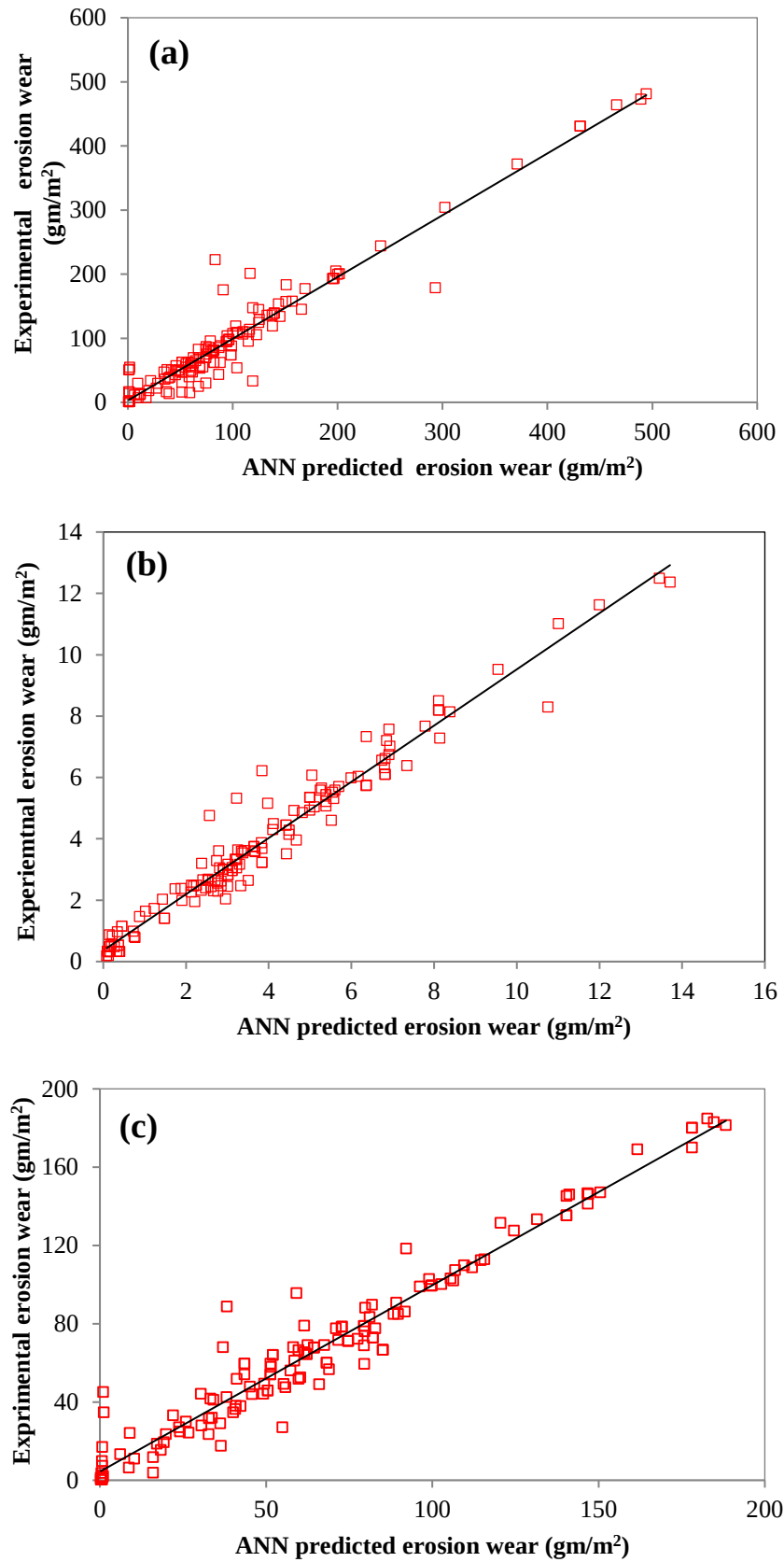


Figure 7.11. Experimental versus ANN predicted results of erosion wear by (a) sand, (b) fly ash, and (c) bottom ash slurry.

The ANN model can be beneficial in future for prediction of erosion wear from a small data set. The benefits and suggestions to use ANN model are discussed as follows:

- The term optimization generally denotes the optimal solution of problem. However in present study, the erosion wear was the output parameter which depends on different properties. From experimental results it was found that the erosion wear increases with increase in velocity, concentration, time. Materials show different erosion wear for impact angle which could not be predictable. Therefore, the erosion wear couldn't be optimized in terms of parametric variations. However, it could be optimized by using prediction from small data set.
- ANN network have optimized the erosion wear by prediction of results from an experimental data set. It was found to be beneficial in saving the cost, material consumption and time to evaluate the erosion wear.
- ANN models are helpful as compared to different other techniques such as computational technique. Computational techniques solve the specific problems which are based on assumptions or ideal conditions. ANN model helps to evaluate the erosion wear utilizing the experimental data.
- The ANN model can be used by increasing the neurons in hidden layer to refine the solution. This will be helpful to predict the data from a small data set such as 50-50%, 70-30%, 60-40% etc. for training and testing-validation.

CHAPTER 8

CONCLUSIONS & FUTURE SCOPE

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CONCLUSIONS & FUTURE SCOPE

Due to the variety of investigations carried out in present study, it is necessary to summarize the key-findings of each objective and to identify the scope of further research in this area. This chapter lists the broad conclusions drawn on the basis of present investigation and recommendations for future work.

8.1 SUMMARY

The present study was conducted to evaluate the erosion wear of different pumping materials and coatings by using different slurries. In present investigation, three different slurries namely fly ash, bottom ash and sand were used. Four different pumping materials namely grey cast iron, stainless steel SS304, SS316L and super duplex stainless steel SDSS2507 were used. High-velocity oxy-fuel (HVOF) process was used to spray the different coating powders on pump materials. The metal composite coating powders used in present investigation were Ni-20Cr₂O₃, WC-10Co-4Cr, Stellite-6, and Colmonoy-88. The WC-10Co-4Cr cermet powder was modified by addition of 3% proportion of Y₂O₃, Mo₂C and ZrO₂ powders. The erosion wear experiments were carried out for pumping materials and different coatings at different rotational speeds of impeller, solid concentrations, time durations, shape factors, impact angles to match the actual conditions in a slurry pot tester.

8.2 CONCLUSIONS

This section includes the conclusions based on the results presented in the previous chapters. Following conclusions have been drawn on the basis of present study:

- Sand particles were found coarser in nature as compared to bottom ash particles whereas fly ash particles were finer in nature. The circularity factor of fly ash particles was higher as compare bottom ash and sand particles.
- Erosion wear results of different pumping materials show that the rank of material type was highest among rotational speed, time and solid concentration (wt. %). Amongst various process parameters the rotational speed was the most influencing factor.
- Erosion wear of different coatings was found to increase non-linearly with increase in time duration, rotational speed and solid concentration whereas it decreases with increase in *CF* value. The erosion wear of different coatings follows power-law relationship with *CF* value. The increment of erosion wear was higher at initial phase of erosion wear

experiments. It can be concluded that erosion wear process affects the particulate properties. The size of particle decreases after erosion wear experiments.

- 3% addition of Y_2O_3 and Mo_2C was helpful to improve the erosion wear resistance of WC-Co-Cr cermet coating. The order of erosion wear is found as: WC-10Co-4Cr+3% Y_2O_3 <WC-10Co-4Cr+3% Mo_2C <WC-10Co-4Cr<WC-10Co-4Cr+3% ZrO_2 .
- Erosion wear resistance of base material was improved by 3.29-3.61 times with deposition of WC-10Co-4Cr. Erosion wear resistance base material was improved 2.96-3.13 times with deposition of WC-10Co-4Cr+3% ZrO_2 . Erosion wear resistance base material was improved by 3.48-3.67 times with deposition of WC-10Co-4Cr+3% Mo_2C . Erosion wear resistance base material was improved by 3.76-3.94 times with deposition of WC-10Co-4Cr+3% Y_2O_3 .
- Sand generates highest erosion wear followed by bottom ash and fly ash. The value of erosion wear was found to increase with increase in circularity factor (CF) value. The exponent of CF value is calculated in the present study that holds good agreement with statement reported by Walker and Humbe (2015).
- Maximum erosion was observed at 30° impact angle arrangement for Stellite-6 and Ni-20Cr₂O₃ coatings whereas at 60° impact angle for Colmonoy-88, Ni-20Al₂O₃ and Al-20TiO₂ coatings. It was found that the Stellite-6 and Ni-20Cr₂O₃ coating shows the ductile erosion wear whereas Colmonoy-88, Ni-20Al₂O₃ and Al-20TiO₂ showed the semi-brittle erosion wear behavior.
- Erosion wear resistance of base material was improved by 2.56-2.63 and 2.84–3.09 times respectively with deposition of Stellite-6 and Colmonoy-88. Erosion wear resistance of base material was improved by 2.56–3.19 times with deposition of Ni-20Cr₂O₃ and Ni-20Al₂O₃. Erosion wear resistance of base material was improved by 1.15–1.75 times with deposition of Al-20TiO₂.
- Microscopically, eroded surface of Stellite-6 showed the microcutting, plastic deformation, ploughing actions with few craters and lips. Colmonoy-88 surface underwent to craters, ploughing, carbide/boride pullout, fractures and intact. Erosion wear mechanisms on eroded surface of Colmonoy-88 were neither purely ductile nor brittle. The Ni-20Cr₂O₃ coating underwent to ploughing, microcutting, craters, ploughing, craters, ductile fractures. Microhills were visualized present on the eroded surface of Ni-20Cr₂O₃ coating at different locations. Simultaneously, the loosely bonded alumina grains were appeared on the surface of Ni-20Al₂O₃ coating by impact of erodent particles.

Furthermore, no crack or splat debonding was observed on the surface which indicates the semi-brittle behavior of the coating. Commonly observed erosion wear mechanisms on the surface of Al-20TiO₂ coating were craters and ductile fractures which shows its semi-ductile behavior.

- Erosion wear was successfully simulated by using an artificial neural network. The percentage error between experimental and ANN predicted erosion wear was found as ± 4.87 , 4.27 and 4.98% for sand, fly ash and bottom ash slurry which indicates the close agreement between neural network and experimental results.
- Pumping materials used in present study are widely used in other hydraulic machinery (such as turbines, pumps, valves, fittings etc.) of hydraulic power plants, chemical industry and marine industry. Therefore, the deposition of ductile and brittle coatings is a better option for durable performance of stainless steels and other materials. Coating–substrate systems must be designed by maintaining the different mechanical properties along with microhardness to control the erosion wear.

8.3 FUTURE SCOPES

This study can be extended in terms of durability of cermet and metal composite coatings under different conditions. It would be more beneficial to further augment the knowledge database by carrying out the further work on following topics:

- Erosion wear studies of cermet and metal composite coatings in other environment such as sea-water applications.
- Investigation on erosion-corrosion study of cermet and metal composite coatings by acidic nature of slurry.
- Comparison of HVOF sprayed cermet and metal composite coatings with other coating deposition processes.
- Extension of studies on cermet and metal composite coatings to erosion-abrasion investigations. Erosion-abrasion occurs in impeller of progressive cavity pumps. Erosion-abrasion analysis of different advanced pump materials can be helpful in improving the life of pumps.
- Extension of studies to lower impact angles-higher velocities, a wider range of impact velocity and solid concentration under different environment.
- To perform CFD analysis of different coatings in pot tester for development of numerical simulation tool. This will save the time required for the in-situ testing and reduce cost.

LIST OF PUBLICATIONS

SCI/SCIE indexed publications

Jashanpreet Singh*, Satish Kumar, Saroj Kumar Mohapatra, *Erosion tribo-performance of HVOF deposited Stellite-6 and Colmonoy-88 micron layers on SS-316L*. Tribology International, June 2018. (Impact Factor: 3.246)
<https://doi.org/10.1016/j.triboint.2018.06.004>

Jashanpreet Singh*, Satish Kumar, Saroj Kumar Mohapatra: *Tribological analysis of WC–10Co–4Cr and Ni–20Cr₂O₃ coating on stainless steel 304*. Wear 2017. 376-377: 1105-1111. (Impact Factor: 2.960)
<http://dx.doi.org/10.1016/j.wear.2017.01.032>

Jashanpreet Singh*, Satish Kumar, Saroj Kumar Mohapatra: *Study on role of particle size in erosion wear of Austenitic steel using Digital Image processing technique*. Institute of Proceedings of Mechanical Engineering, Part J: Journal of Engineering Tribology. (Impact Factor: 1.318)
<http://dx.doi.org/10.1177/1350650118794698>

Jashanpreet Singh*, Satish Kumar, Saroj Kumar Mohapatra: *Erosion wear performance of Ni-Cr-O and NiCrBSiFe-WC(Co) composite coatings deposited by HVOF technique*. Surface tribology of HVOF sprayed Ni-Cr₂O₃ and NiCrBSiFeCoWC. Industrial lubrication and Tribology 2018 **(Accepted)**. (Impact Factor: 0.763). (Impact Factor: 0.763)
<http://dx.doi.org/10.1108/ILT-04-2018-0149>

Jashanpreet Singh*, Satish Kumar, Saroj Kumar Mohapatra: *An erosion and corrosion study on thermally sprayed WC-Co-Cr powder synergized with Mo₂C/Y₂O₃/ZrO₂ feedstock powders*. Wear 2019 **(Accepted)**. (Impact Factor: 2.960)
<https://doi.org/10.1016/j.wear.2019.01.082>

Scopus indexed/proceedings

Jashanpreet Singh, Satish Kumar*, Saroj Kumar Mohapatra, Sagar Kumar: *Shape simulation of solid particles by digital interpretations of scanning electron micrographs using IPA technique*. Materials Today: Proceedings 2018; 5, 17786–17791.

Jashanpreet Singh*, Satish Kumar, Gurprit Singh: *Taguchi's approach for optimization of Tribo-resistance parameters for SS304*. Materials Today: Proceedings 2017; 5 (2018) 5031–5038.

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APPENDIX-I

EROSION WEAR OF WC-10CO-4Cr CERMET COATINGS

Weight loss data WC-10CO-4Cr cermet coatings for sand slurry

N (rev/min)	C (wt. %)	T (min)	α (° degree)	Weight loss from sample specimen (in gm)			
				Pure	3% Y ₂ O ₃	3% Mo ₂ C	3% ZrO ₂
600	30	180	0	0.00226	0.00148	0.00175	0.00256
900	30	180	0	0.00247	0.00157	0.00192	0.00307
1200	30	180	0	0.00270	0.00163	0.00202	0.00337
1500	30	180	0	0.00297	0.00167	0.00206	0.00340
1500	30	180	0	0.08740	0.06243	0.06662	0.09326
1500	40	180	0	0.10200	0.07034	0.07695	0.10926
1500	50	180	0	0.11600	0.07785	0.08623	0.13343
1500	60	180	0	0.14880	0.09725	0.10146	0.16265
1500	60	90	0	0.02975	0.01666	0.02059	0.03404
1500	60	120	0	0.06584	0.03667	0.04831	0.08330
1500	60	150	0	0.10411	0.05830	0.07714	0.12590
1500	60	180	0	0.13867	0.08713	0.10146	0.16265
1500	60	180	0	0.13867	0.08713	0.10146	0.16265
1500	60	180	30	0.19414	0.13291	0.13069	0.19518
1500	60	180	45	0.23297	0.17411	0.19604	0.22445
1500	60	180	60	0.27957	0.21068	0.25485	0.26485

Weight loss data WC-10CO-4Cr cermet coatings for fly ash slurry

N (rev/min)	C (wt. %)	T (min)	α (° degree)	Weight loss from sample specimen (in gm)			
				Pure	3% Y ₂ O ₃	3% Mo ₂ C	3% ZrO ₂
600	30	180	0	0.00021	0.00014	0.00016	0.00024
900	30	180	0	0.00029	0.00021	0.00024	0.00037
1200	30	180	0	0.00045	0.00028	0.00033	0.00057
1500	30	180	0	0.00064	0.00054	0.00062	0.00075
1500	30	180	0	0.00064	0.00068	0.00062	0.00075
1500	40	180	0	0.00126	0.00129	0.00122	0.00148
1500	50	180	0	0.00250	0.00249	0.00242	0.00293
1500	60	180	0	0.00525	0.00489	0.00508	0.00615
1500	60	90	0	0.00380	0.00360	0.00369	0.00450
1500	60	120	0	0.00429	0.00407	0.00417	0.00507
1500	60	150	0	0.00481	0.00456	0.00467	0.00561
1500	60	180	0	0.00525	0.00489	0.00508	0.00615
1500	60	180	0	0.00525	0.00489	0.00508	0.00615
1500	60	180	30	0.00788	0.00645	0.00671	0.00812
1500	60	180	45	0.01040	0.00852	0.00886	0.01072
1500	60	180	60	0.01373	0.01073	0.01169	0.01415

Weight loss data WC-10CO-4Cr cermet coatings for bottom ash slurry

N (rev/min)	C (wt. %)	T (min)	α (° degree)	Weight loss from sample specimen (in gm)			
				Pure	3% Y ₂ O ₃	3% Mo ₂ C	3% ZrO ₂
600	30	180	0	0.00073	0.00046	0.00057	0.00095
900	30	180	0	0.00109	0.00065	0.00079	0.00132
1200	30	180	0	0.00142	0.00088	0.00106	0.00172
1500	30	180	0	0.00172	0.00108	0.00136	0.00209
1500	30	180	0	0.05159	0.03251	0.04069	0.06777
1500	40	180	0	0.07727	0.05135	0.05617	0.09339
1500	50	180	0	0.10087	0.06253	0.06954	0.11633
1500	60	180	0	0.13412	0.07347	0.08670	0.14368
1500	60	90	0	0.02704	0.01481	0.01748	0.02897
1500	60	120	0	0.06125	0.03352	0.04368	0.07152
1500	60	150	0	0.10096	0.05549	0.06873	0.11145
1500	60	180	0	0.13412	0.07347	0.08670	0.14368
1500	60	180	0	0.13412	0.08670	0.07347	0.14368
1500	60	180	30	0.16252	0.10549	0.10373	0.15490
1500	60	180	45	0.18490	0.13819	0.15053	0.17814
1500	60	180	60	0.22188	0.16720	0.18033	0.21020

APPENDIX-II

EROSION WEAR OF METAL COMPOSITE COATINGS

Weight loss data metal composite coatings for sand slurry

N (rev/min)	C (wt. %)	T (min)	α (° degree)	Weight loss from sample specimen (in gm)				
				Colmonoy-88	Stellite-6	Ni-20Cr ₂ O ₃	Ni-20Al ₂ O ₃	Al-20TiO ₂
600	30	180	0	0.01098	0.01603	0.01951	0.05980	0.08715
900	30	180	0	0.04586	0.06328	0.06809	0.09418	0.11622
1200	30	180	0	0.08176	0.09902	0.10007	0.12086	0.14658
1500	30	180	0	0.10550	0.12600	0.12600	0.13820	0.16642
1500	30	180	0	0.10237	0.10550	0.11400	0.13820	0.16642
1500	40	180	0	0.12716	0.14070	0.16000	0.21201	0.32984
1500	50	180	0	0.13744	0.15384	0.20142	0.25526	0.49521
1500	60	180	0	0.15887	0.17647	0.23585	0.33177	0.72828
1500	60	90	0	0.11400	0.11507	0.12607	0.18532	0.40680
1500	60	120	0	0.13567	0.14907	0.16000	0.23255	0.51048
1500	60	150	0	0.14687	0.16727	0.20142	0.28552	0.62676
1500	60	180	0	0.15887	0.17647	0.23585	0.33177	0.72828
1500	60	180	0	0.23585	0.17647	0.15887	0.33177	0.72828
1500	60	180	30	0.16884	0.24480	0.21086	0.33476	0.78654
1500	60	180	45	0.17568	0.24270	0.20768	0.33777	0.82587
1500	60	180	60	0.18535	0.19680	0.13872	0.34081	0.83413

Weight loss data metal composite coatings for fly ash slurry

N (rev/min)	C (wt. %)	T (min)	α (° degree)	Weight loss from sample specimen (in gm)				
				Colmonoy-88	Stellite-6	Ni-20Cr ₂ O ₃	Ni-20Al ₂ O ₃	Al-20TiO ₂
600	30	180	0	0.00373	0.00402	0.00466	0.00564	0.00692
900	30	180	0	0.00400	0.00462	0.00620	0.00745	0.00931
1200	30	180	0	0.00481	0.00557	0.00759	0.00941	0.01148
1500	30	180	0	0.00544	0.00647	0.00842	0.01150	0.01369
1500	30	180	0	0.00427	0.00440	0.00475	0.00576	0.00693
1500	40	180	0	0.00471	0.00499	0.00615	0.00757	0.00908
1500	50	180	0	0.00509	0.00570	0.00746	0.00945	0.01137
1500	60	180	0	0.00544	0.00647	0.00842	0.01150	0.01369
1500	60	90	0	0.00172	0.00207	0.00317	0.00592	0.00961
1500	60	120	0	0.00320	0.00358	0.00538	0.00862	0.01155
1500	60	150	0	0.00433	0.00549	0.00747	0.01074	0.01313
1500	60	180	0	0.00544	0.00647	0.00842	0.01150	0.01369
1500	60	180	0	0.00544	0.00647	0.00842	0.01150	0.01369
1500	60	180	30	0.00778	0.00890	0.01165	0.01610	0.02024
1500	60	180	45	0.00909	0.00936	0.01239	0.01815	0.02270
1500	60	180	60	0.01011	0.00909	0.01166	0.01858	0.02313

Weight loss data metal composite coatings for bottom ash slurry

N (rev/min)	C (wt. %)	T (min)	α (° degree)	Weight loss from sample specimen (in gm)				
				Colmonoy-88	Stellite-6	Ni-20Cr ₂ O ₃	Ni-20Al ₂ O ₃	Al-20TiO ₂
600	30	180	0	0.01046	0.01527	0.02702	0.05526	0.08300
900	30	180	0	0.04030	0.04508	0.06147	0.07619	0.10393
1200	30	180	0	0.06437	0.06899	0.08349	0.09823	0.12272
1500	30	180	0	0.08531	0.08792	0.10512	0.11517	0.13868
1500	30	180	0	0.08531	0.08792	0.10512	0.11517	0.13868
1500	40	180	0	0.09419	0.09979	0.12308	0.15143	0.19517
1500	50	180	0	0.10181	0.11395	0.14920	0.18908	0.24757
1500	60	180	0	0.10881	0.12605	0.16846	0.23698	0.30071
1500	60	90	0	0.03097	0.03728	0.05700	0.09266	0.20340
1500	60	120	0	0.05766	0.06446	0.09688	0.13990	0.23836
1500	60	150	0	0.08701	0.09875	0.13446	0.19339	0.27288
1500	60	180	0	0.10881	0.12605	0.16846	0.23698	0.30071
1500	60	180	0	0.10881	0.12605	0.16846	0.23698	0.30071
1500	60	180	30	0.11982	0.13706	0.17948	0.24799	0.31172
1500	60	180	45	0.13431	0.13101	0.17343	0.25404	0.31777
1500	60	180	60	0.13474	0.12116	0.15553	0.24770	0.30839

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*“PhD is awarded to a single hand but there are many hands
which works behind to achieve the final goal of PhD”*

- Jashanpreet Singh