STUDY OF THE SLURRY EROSION BEHAVOIUR IN HYDROPOWER PLANTS

A Thesis Report Submitted
in partial fulfillment of the requirements for
the award of degree of

MASTER OF ENGINEERING
IN
PRODUCTION AND INDUSTRIAL ENGINEERING

Submitted by

Randeep Singh
Roll No.: 800982023

Under the Guidance of

Dr. S.K. Mohapatra
Sr. Professor (MED) & Dean of Academic Affairs

DEPARTMENT OF MECHANICAL ENGINEERING
THAPAR UNIVERSITY
PATIALA-147004, INDIA.

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DECLARATION

I hereby certify that the work which is being presented in the report entitled, **"STUDY OF THE SLURRY EROSION BEHAVOIUR IN HYDROPOWER PLANTS"**, in partial fulfillment of the requirements for the award of degree of Master of Engineering in Mechanical Engineering with specialization in **PRODUCTION AND INDUSTRIAL ENGINEERING** submitted in **Mechanical Engineering Department** of Thapar University, Patiala, is an authentic record of my own work carried out under the supervision of **Dr. S.K. Mohapatra** and refers other researcher's works which are duly listed in the reference section.

The matter presented in this thesis has not been submitted for the award of any other degree of this or any other university.

Date: 14/7/11

(Randeep Singh)

Place: Patiala

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

Supervisor:

Dr. S.K. Mohapatra
Dean of Academic Affairs
Thapar University,Patiala

Counter signed by

Dr. Ajay Batish
Professor & head
Mechanical Engineering Department
Thapar University, Patiala

Dr. S.K. Mohapatra
Dean of Academic Affairs
Thapar University,Patiala

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ABSTRACT

Hydropower plants suffer from silt erosion of underwater parts. Particularly in monsoon season, when 90% of the silt particle size is 0.2mm and contains quartz with hardness 7-8 on Moh's scale value. The various parts of the plant are subjected to an environment that contains silt having particles (MgO, CaO, Al_2O_3, SiO_2, clays, volcanic ash and the like) carried by water. These sediments are formed by the fragmentation of rocks, land erosion and landslides due to heavy rain in monsoon season.

It is not cost effective to construct any arrangement to remove this size of silt particles from the running water. The problem of erosion underwater parts of the hydropower plant and measures to minimize such damages has been constantly engaging the attention of hydropower engineers and manufacturers of equipment. Presently Baira Siul project (3x66MW) Himachal Pradesh[NHPC] handles nearly 10,000 tonnes of silt per day, per machine during critical monsoon days. Material loss in guide vanes alone is 10% by weight. Stainless steels are widely used in hydroelectric power plants due to their good corrosion resistance properties and acceptable resistance to solid particle erosion, since many components are in contact with aqueous solution containing hard particles that impact against the surface causing significant materials loss.

The present works is to study the erosion wear behavior of hydro turbine material, Stainless steel with and without coating. The base material is coated with three powders to enhance it surface properties. HVOF thermal spray coating technique is used for coating. The various coatings are WC-Co-Cr, $Cr_2C_3 + NiCr$ and diamalloy. The Jet type erosion tester is used to study the erosion wear of base material with and without Coatings with different compositions. Sand for the present investigation was collected from Naptha Jakhri power plant, H.P. It is experimentally observed that HVOF thermal spray coating on to 16/5 steel helps in reducing the erosion wear of hydro turbine materials. WC-Co-Cr coating shows the best resistance to silt erosion.

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ABBREVATIONS

16/5 steel	16Cr 5Ni turbine steel
SEM	Scanning Electron Microscopy
PSD	Particle size distribution
HVOF	High Velocity Oxy Fuel
PVD	Physical Vapor Deposition
D Gun	Detonation Thermal Spray Technique

NOMENCLATURE AND SYMBOLS

Symbol	Description
mg	Milligram
t	Time, seconds
T	Temperature, °C
%	Percentage
mm	Millimeter
µm	Micro meter
W_b	Weight of beaker
W_{bs}	Weight of beaker and solid
W_{bw}	Weight of beaker and water
W_{bsw}	Weight of beaker, solid and water
°	Angle, (Degree)

CHAPTER-1

INTRODUCTION

Hydropower is the most important of the entire renewable source for electrical power production worldwide. About 19% of the planet's electricity is produced by hydropower stations. Utilizing low cost, renewable energy system is the requirement of the world today to reduce the effect of global warming.

India is blessed with immense amount of hydro-electric potential and ranks 5th in terms of exploitable hydro-potential on global scenario. Presently in India the total installed capacity including all resources is 173,626.40MW, of which the share of the hydro energy is 22% (ministry of power). India is blessed with immense amount of hydroelectric potential and only 17% of total potential is being effectively used till now. Hence, a lot of importance is needed to develop the hydropower potential.

1.1 HYDROPOWER PLANT

Hydropower plant is house for the production of electrical power through the use of the gravitational force of falling or flowing water. It is the most widely used form of renewable energy.Once a hydroelectric complex is constructed, the project produces no direct waste. Approximately 20% of the world's electricity, and accounted for about 88% of electricity from renewable sources.First hydro-electric station was probably established in America in 1882 and thereafter development took place very rapidly. In India the first major hydro-electric development in Mysore was commissioned in 1902of 4.5 MW capacity named as Sivasaroudram Scheme. In 1914 a hydro-power plant named Khopoli project of 50 MW capacity was commissioned in Maharashtra, The hydro- power capacity, upto 1947, was nearly 500 MW.

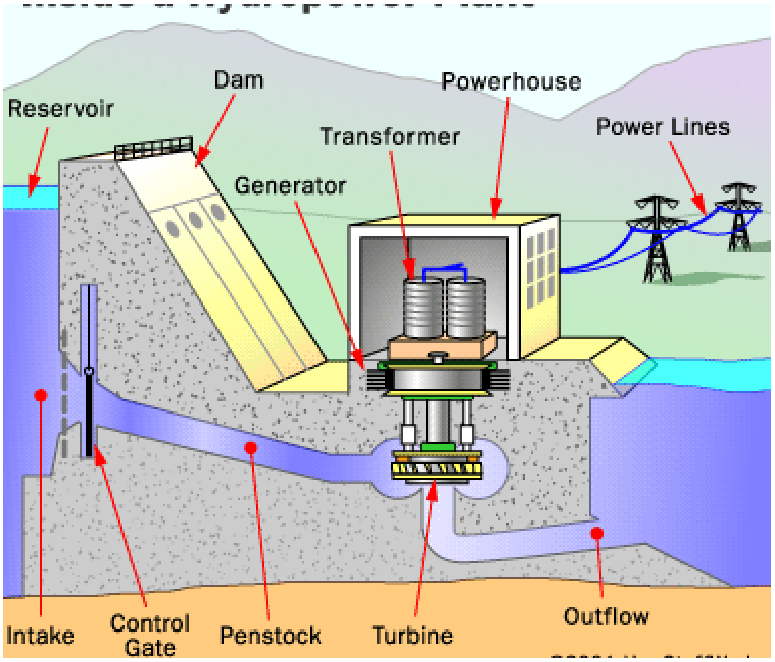

Figure 1.1 Model of Hydropower plant

In hydro-electric plants energy of water is utilized to move the turbines which in turn run the electric generators. The energy of water utilized for power generation may be kinetic or potential. The kinetic energy of water is its energy in motion and is a function of mass and velocity, while the potential energy i.e. a function of the difference in level/head of water between two points. In either case continuous availability of water is a basic necessity; to ensure this, water collected in natural lakes and reservoirs at high altitudes may be utilized or water may be artificially stored by constructing dams across flowing streams. The ideal site is one in which a good system of natural lakes with substantial catchments area, exists at a high altitude. Rainfall is the primary source of water and depends upon such factors as temperature, humidity, cloudiness, wind etc. The usefulness of rainfall for power purposes further depends upon several complex factors which include its intensity time distribution, topography of land etc. However it has been observed that only a small part of the rainfall can actually be utilized for power generation. A significant part is accounted for by direct evaporation, while another similar quantity seeps into the soil and forms the underground storage. Some water is also absorbed by vegetation. Thus, only a part of water falling as rain actually flows over the ground surface as direct run off and forms the streams which can be utilized for hydro-schemes.

First hydro-electric station was probably started in America in 1882 and thereafter development took place very rapidly. In India the first major hydro-electric development of 4.5 MW capacity named as Sivasaroudram Scheme in Mysore was commissioned in 1902. In 1914 a hydro-power plant named Khopoli project of 50 MW capacity was commissioned in Maharashtra, The hydro-power capacity, upto 1947, was nearly 500 MW.

Hydro (water) power is a conventional renewable source of energy, which is clean, free from pollution and generally has a good environmental effect. However the following factors are major obstacles in the utilisation of hydro-power resources:

(i) Large investments
(ii) Long gestation period
(iii) Increased cost of power transmission.

Next to thermal power, hydro-power is important in regard to power generation. The hydro-electric power plants provide 30 per cent of the total power of the world. The total hydro-potential of the world is about 5000 GW. In some countries (like Norway) almost total power generation is hydro based.

Earlier hydro-electric plants have been used as exclusive source of power, but the trend is towards use of hydropower in an interconnected system with thermal stations. As a self-contained and independent power source, a hydro-plant is most effective with adequate storage capacity other- wise the maximum load capacity of the station has to be based on minimum flow of stream and there is a great wastage of water over the dam for greater part of the year. This increases the per unit cost of installation. By inter connecting hydro-power with steam; a great deal of saving in cost can be effected due to:

- reduction in necessary reserve capacity,
- diversity in construction programmes
- higher utilization factors on hydroplants
- higher capacity factors on efficient steam plants

In an interconnected system the base load is supplied by hydropower when the maximum/low demand is less than the stream flow while steam supplies the peak. When stream flow is lower than the maximum demand the hydro plant supplies the peak load and steam plant the base load.

1.1.1ESSENTIAL COMPONENT OF HYDRO-ELECTRIC POWER PLANT

Essential components of a hydro electric power plant (shown in figure 1.1) are as follows:

Storage reservoir: The water available from an attachment area is stored in a reservoir so that it can be run to utilize the turbine for producing power according to requirement.

Dam with control work: Dam is a structure erected a suitable site to provide for the storage of the water and created head. Dam may be built to make an artificial reservoir from the valley or it may be created in a river to control the flowing water.

Water ways: Water ways is a passage through the water carried from the storage reservoir to the power houses. It consists of tunnel control, force pipe and penstock. Tunnel is a water passage made by cutting to mountain to save distance for bay in an enlarged section canal spread to accommodate the required width of Intake its function is to store temporarily water rejected to plant.

Penstock: It is a pipe of large diameter carrying water under pressure from storage top tank.

Power house: It is a building to house the turbine penstock and others for operating the machines.

Spill way: It is a safety valve for dam.Water after a certain level in the reservoir overflows through spill way without allowing the increase in water level in the reservoir particularly during rainy season.

Surge tank: This helps in reducing the pressure surges developed due to sudden back flow of water as load on the turbine it reduced. Otherwise penstock will be damaged by the water hammer produced by sudden back flow.

Prime mover: It converts the potential energy of water to the mechanical energy.

Head race: Water surface of reservoir level is called head race.

Tail race: Water passing through turbine is discharged through tail race.

Hydropower plants located in northern region suffer from silt erosion of underwater parts. Particularly in monsoon season, when 90% of the silt particle size is 0.2mm and contains quartz with hardness 7-8 0n Moh's scale. The various parts of the plant are subjected to an environment that contains silt having particles (for egMgO, CaO, $Al_2O_{3,}, SiO_2$, clays, volcanic ash and the like) carried by water. These sediments are formed by the fragmentation of rocks, land erosion and landslides due to heavy rain in monsoon season.

It is not cost effective to construct any arrangement to remove this size of silt particles from the running water. The problem of erosion underwater parts of the hydropower plant and measures to minimize such damages has been constantly engaging the attention of hydropower engineers and manufacturers of equipment.

1.2 WEAR

Wear is defined as the progressive volume loss of material from target surface. It may be due to erosion, abrasion or corrosion. The wear due to corrosion is caused by chemical reactions, which can be prevented by adopting suitable measures. The wear due to erosion or abrasion can be minimized by controlling the affecting parameters.

1.2.1 TYPES OF WEAR

a)Adhesive Wear

Adhesive wear is the only universal form of wear.It arises from the fact that, during sliding, regions of adhesive bonding, called junctions, form between the sliding surfaces. If one of these junctions does not break along its original interface, then a chunk from one of the sliding surfaces will have been transferred to the other surface. In this way, an adhesive wear particle will have been formed. Initially adhering to the other surface, adhesive particles soon become loose and can disappear from the sliding system. One of the significant things about adhesive wear is that at the interface, or the point where it touches another metal surface, it must be very hot in order for the micro welding to take place at all. Adhesive wear is because of microscopic welding. The heat produced at the contact interface is very high (near the melting point of the two metals touching each other).

b) Abrasive Wear

Abrasive wear is produced by a hard, sharp surface sliding against a softer one and digging out a groove. The abrasive agent may be one of the surfaces or it may be a third component (such as sand particles) Abrasive wear coefficients are large as compared to adhesive wear. Thus, the introduction of abrasive particles into a sliding system can greatly increase the wear rate. On the abrasive specimen, the surface shows a scratched appearance from hard particles digging into it as they were moved across the surface.

c) Corrosive Wear

Corrosive wear arises when a sliding surface is in a corrosive environment, and the sliding action continuously removes the protective corrosion layer, thus exposing fresh surface to further corrosive attack. Corrosive wear occurs as a result of chemical reaction on a wearing surface. The most common type of corrosion is mainly due to reaction between metal and oxygen. These oxides are wiped away with the flow and cause pitting of the surfaces. Corrosion is accelerated as impacted surfaces are exposed to slurry chemistry.

d) Surface Fatigue Wear

Surface fatigue is a process by which the surface of a material is weakened by cyclic loading, which is one type of general material fatigue. Surface fatigue wear occurs as result of the formation and growth of cracks. It is the main form of wear of rolling devices such as ball bearings, wheels on rails, and gears. During continued rolling, a crack forms at or just below the surface and gradually grows until a large particle is lifted right out of the surface.

e) Erosive wear

Erosive wear is the dominant process and can be defined as progressive loss of original material from a solid surface due to mechanical interaction between the surface and a fluid, a multi-component fluid or impinging liquid or solid particle. Erosion involves the transfer of kinetic energy to the surface. This means that in erosion material removal is a function of particle velocity squared to higher power. Erosive wear depends on the predominant impact angle of particle impingement with the material surface. Impact angle will vary from 0 to 90 degrees and depend on both fluid particle and particle- particle interaction. This type of wear can be found on impellers and volute casing in slurry pumps, angled pipe bends, turbines, pipes and pipe fitting, nozzles, burners etc. The material loss due to erosion increases with the increase in kinetic energy of the particles impacting at the target surface. The volume loss due to erosion is a troublesome problem foe slurry transportation systems e.g. mineral transport systems, ash disposal systems. The erosion wear due to the air borne particles in some devices such as jet planes and turbines is also significant due to very high impact velocity. It is thus a challenging task to control the erosion wear in many engineering applications. The material removal due to erosion is caused by two dominant mechanisms namely brittle fractures and platelet deformations. In brittle type material, the solid particles impacting on the target surface forms cracks in longitudinal and lateral directions. These cracks propagate due to impact of succeeding particles and broken materials pieces will be carried out by flowing fluid. The material removal rate due to brittle fracture increases with increase in normal component if the particle velocity and thus the brittle type material show maximum ear near normal impact angles. In Platelet mechanism, the impact of solid particles deforms the target surface to forms hills and valleys. The repeated impacts of particles remove the material and forms crater at the surface. This mechanism along with micro-cutting and chipping dominates in ductile type materials, which show the maximum wear in the impact angle range of 20-40 degree. Apart from the target surface characteristics like brittle or ductile type, many other parameters such as solid particles, carrier fluid, flow conditions etc. affect the erosion wear. It is, therefore, difficult to estimate wear for a given operating conditions.

1.2.2 TYPES OF EROSION WEAR

Erosion can be classified into different types depending upon interaction taking place between the target surface and the impacting substance.

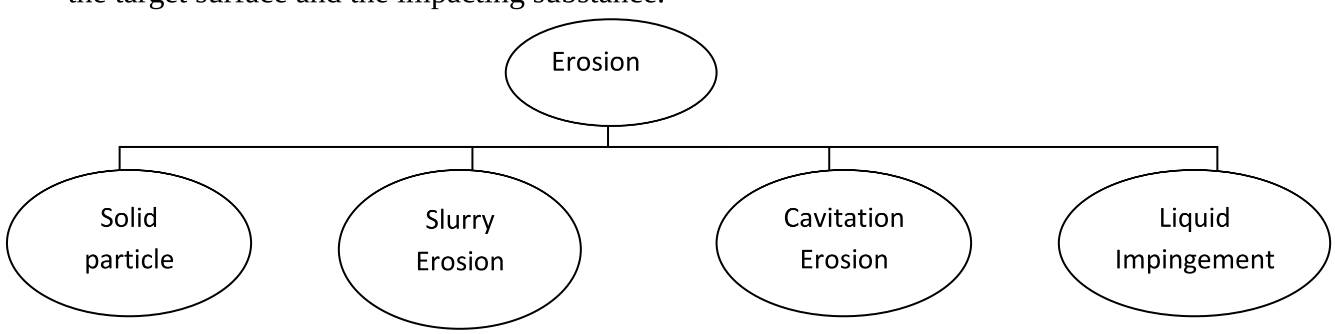

Figure 1.2 Types of erosion wear

a) Solid Particle Erosion is the loss of material that results from repeated impact of small, solid particles entrained in air/gas. In some cases SPE is a useful phenomenon, as in sandblasting and high-speed abrasive cutting, but it is a serious problem in many engineering systems, including steam and jet turbines, pipelines and valves carrying particulate matter. Solid particle erosion is to be expected whenever hard particles are entrained in a gas medium impinging on a solid at any significant velocity.

b) Cavitation Erosion is defined as the repeated nucleation, growth, and violent collapse of cavities, or bubbles, in a liquid. In practice, all liquids contain gaseous, liquid, and solid impurities, which act as nucleation sites for the cavities. When the liquid that contains cavities is subsequently subjected to compressive stresses, that is, to higher hydrostatic pressure, these cavities will collapse. This collapse is directly responsible for the erosion process.

c) Liquid Impingement Erosion has been defined as progressive loss of original material from a solid surface due to continued exposure to impacts by liquid drops or jets. Liquid impingement erosion is related to repeated impacts or collisions between the surface being eroded and small discrete liquid bodies. The significance of the discrete impacts is that they generate impulsive contact pressures on the solid target, far higher than those produced by steady flows thus, the endurance limit and even the yield strength of the target material can easily be exceeded, thereby causing damage by purely mechanical interaction.

d) Slurry Erosion is defined as that type of wear, or loss of mass, that is experienced by a material exposed to a stream of slurry. This erosion occurs either when the material moves at a certain velocity through the slurry or when the slurry moves past the material at a certain velocity. Slurries erode by the action of abrasive particles in the liquid which results in the failure of the surface of material in one or another mode depending upon the conditions to which the system is exposed. Slurry erosion is a serious problem for the industries, which deals with the liquids having solid particles entrained in them. When such a mixture of liquid and solid particles termed as slurry come in contact with the machine element, the removal of material takes place from the surface making the component redundant from the surface.

1.2.3 FACTORS EFFECTING SLURRY EROSION

There are large number of factors that lead towards the degradation of the surface and loss of material due to slurry erosion. These are the factors that decide which type of erosion mechanism will be predominating in the material removal process. Factors can be categorized as below:

- Factors depending on the operating conditions. For e.g. Velocity, impact angle, concentration, temperature etc.
- Factors that depend on the erodents. For e.g. particle size, particle shape, hardness
- Factors that depends upon the properties of target surface. For e.g. hardness, microstructure, mechanical properties etc.

The effect of these various parameters have been studied by various researchers and results of those has been discussed in literature review, next chapter.

1.3 SLURRY EROSION OF HYDRO-TURBINE MATERIAL.

All hydropower plant suffers from silt erosion of underwater parts. Various components of hydroelectric power plant are subjected to an environment that contains silt having particles (like MgO, CaO,$Al_2O_{3,}$, SiO_2, clays, volcanic ash and the like) carried by water. Sediments are formed by the fragmentation of rocks, land erosion and landslides due to flow of water. The Baira Siul project (3x66MW) in Himachal Pradesh, for instance, handles nearly 10,000 tonnes of silt per day, per machine during critical monsoon days. Material loss in guide vanes alone is 10% by weight [NHPC]. The problem of erosion of underwater parts and measures to minimize such damages has been constantly engaging the attention of hydropower engineers and manufactures of equipments.

Figure 1.3 Eroded blades at Salal & BairaSiul Power Stations [NHPC]

Before 1950's cast iron was used for turbine components, which was later replaced by cast steels. Now a days, Stainless steels are widely used in hydroelectric power plants due to their good corrosion resistance properties and acceptable resistance to solid particle erosion, since many components are in contact with aqueous solution containing hard particles that impact against the surface causing significant materials loss. The magnitude of the damage caused is a consequence of the amount, type, and size of particles in flow, together with mechanical properties of the surface, physical-chemical properties of the water and operating conditions.

Slurry erosion problems are particularly important during rainy season due to the increase in the number of solid particles impacting the surface, especially in systems where an exhaustive filtration process is not possible. For instance the Francis turbines installed in a north-western Colombia, suffered changes in surface texture and loss adjustment between the liners and the spiral case due to intensive erosion wear [Santa et al 2007]. For minimum damage, the runner rotor material should be resistant to corrosion by the liquid. Other desirable characteristics of material are:

- High tensile strength
- High fatigue strength

- High hardness
- High resilience

Due to thin layer of chromium oxide on their surfaces, the stainless steels exhibits better properties that carbon steels. Most commonly approximately 12% of Cr is used in steel used in fabrication of turbine parts. Cr. Selection of proper steel for the underwater turbine parts operating in silty water is important for ensuring their long service life. The material should have good erosion resistance. Commonlyusedmaterials for different parts of turbine are given below in table 1.1.

Table 1.1Commonly recommended turbine material (Naidu 1999)

S. No.	Components	Materials
1	Runner	ASTM743-13Cr5Ni, SEW 410-16Cr5Ni
2	Labyrinth Seals	ASTM743-13Cr5Ni, 18Cr10Ni, SEW 410-16Cr5Ni
3	Guide vane	ASTM743-13Cr5Ni
4	Liner	18Cr10Ni
5	Tubes for bearing coolers	Cupro-Nickel (80%Cu, 20%Ni)
6	Rubber seals	Neoprene synthetic rubber
7	Draft tube	SEW 410-16Cr5Ni, W-1.0566

Among all the options 13Cr4Ni and 16Cr5Ni are most widely used in turbine industry. Both 13Cr4Ni and 16Cr5Ni are austenitic-martensitic steel with δ-ferrite and about 20-25% stable austenite. The normalization followed by annealing at 580 ℃ creates tough structure with martensite. Corrosion résistance is satisfactory in both steels and cavitations' resistance is found better in both, but 16Cr5Ni shows better than 13Cr4Ni. This makes16Cr5Ni steel first choice in modern turbine industry.

1.3.1CONTROLLING ACTIONS FOR SILT EROSION

Some controlling measures have to be taken to reduce the flow of silt in order to reduce the erosion of hydro turbine parts. In 2001 an international conference was organized by central board of irrigation and power to discuss on silt erosion problem in hydropower plant. The various proposed possible solutions were:

- ✓ Catchment area treatment
- ✓ Effective desilting arrangement
- ✓ Use of silt resistant equipments.

Despite of the use of above mentioned controlling measures, it is practically impossible to catch silt particles less than 0.25μm.Beside the usage of above mentioned methods, some another techniques has to be followed to protect various underwater parts of the generating unit from wear. The various approaches like improved design, use of erosion resistant material can reduce the effect of silt.The use of surface coating can also help to limit the problem. The federal highway administration conducted a 6.5 years study in marine environments using 47 coating systems. The tests project a 60 year life for 85/15 Zn Al metalizing coatings. They further conclude that metalized systems "consistently provided the best corrosion protection performance". However, only few studies have been reported on the use of this process for hydraulic turbine applications. And there is a further need to investigate the slurry erosion performance of coatings for this application.

1.4 SURFACE COATING TECHIQUES

As other controlling measures are not that much effective, so some other techniques have to be followed. The service life of any component can be improved by providing a protective coating on the surface exposed to solid particle impact. Most of the investigators have used different methods to improve the surface properties for decreasing the erosion wear and thus to increase the service life of components. Commonly used surface coating techniques are as follows:

- ✓ Electroplating
- ✓ Physical vapour deposition
- ✓ Chemical vapour deposition
- ✓ Thermal spray

1.4.1 ELECTROPLATING

Electroplating is also called electrodeposition. Electrodeposition is the process of producing a coating, usually metallic, on a surface by the action of electric current. The deposition of a metallic coating onto an object is achieved by putting a negative charge on the object to be coated and immersing it into a solution which contains a salt of the metal to be deposited. The metallic ions of the salt carry a positive charge and are thus attracted to the object. When they reach the negatively charged object (that is to be electroplated), it provides electrons to reduce the positively charged ions to metallic form. Figure 1.4 is a schematic presentation of an electrolytic cell for electroplating.

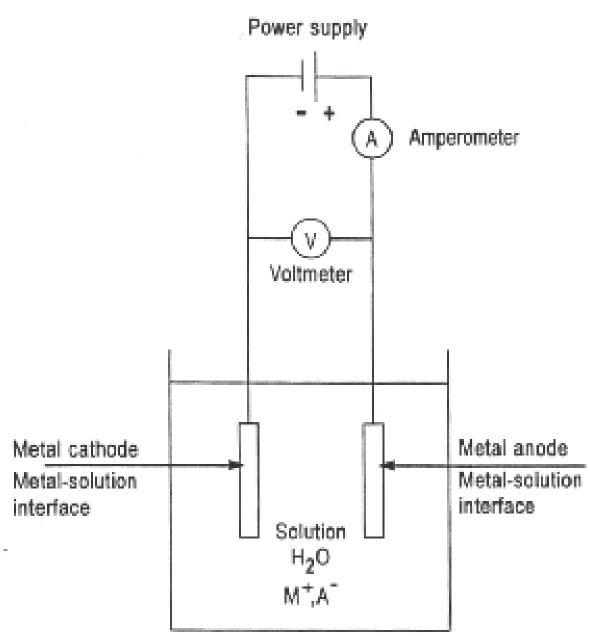

Figure 1.4 Schematics of an electroplating process

Advantages:

- Simple, well-understood technology
- Only used for good conductors of electricity.

Disadvantages:

- Obtaining a uniform thickness with electroplating is difficult
- Slow rate of deposition

1.4.2 PHYSICAL VAPOR DEPOSITION

The basic mechanism of physical vapour deposition is an atom by atom transfer of material from the solid phase to the vapour phase and back to the solid phase, gradually building a film on the surface to be coated. In the case of reactive deposition, the depositing material reacts with a gaseous environment of co-deposited material to form a film of compound material, such as a nitride, oxide, carbide or carbonitride.

The three fundamental steps include:

- ✓ Vapour phase generation from coating material
- ✓ The transfer of the vapour phase from source to substrate
- ✓ Deposition and film growth on the substrate

Advantages:

- More environmentally friendly than traditional coating processes
- Coatings are of better quality than electroplating

Disadvantages:

- Requires a cooling water system to dissipate large heat loads.
- Some PVD technologies typically operate at very high temperatures and vacuums, requiring special attention by operating personnel.
- High capital costs.

1.4.3CHEMICAL VAPOR DEPOSITION

Chemical vapor deposition is used to grow a thin layer of advanced materials on the surface of a substrate. In a typical CVD process, the substrate is exposed to one or more volatile precursors, which react and/or decompose on the substrate surface to produce the desired deposit.

In this process, the substrate is placed inside a reactor to which a number of gases are supplied. The fundamental principle of the process is that a chemical reaction takes place between the source gases. The product of that reaction is a solid material with condenses on all surfaces inside the reactor.

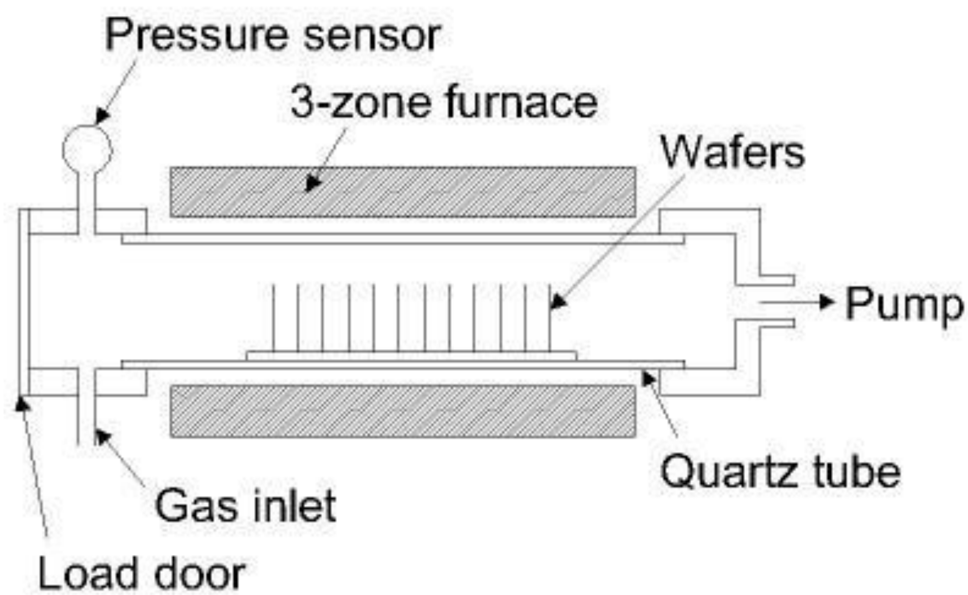

Figure 1.5 Schematic diagram of CVD process

1.4.4 THERMAL SPRAY

Thermal spraying techniques are coating processes in which melted (or heated) materials are sprayed onto a surface. The "feedstock" (coating precursor) is heated by electrical (plasma or arc) or chemical means (combustion flame). Thermal spraying can provide thick coatings (approx. thickness range is 20 micrometers to several mm, depending on the process and feedstock), over a large area at high deposition rate as compared to other coating processes such as electroplating, physical and chemical vapour deposition. Coating materials available for thermal spraying include metals, alloys, ceramics, plastics and composites. They are fed in powder or wire form, heated to a molten or semimolten state and accelerated towards substrates in the form of micrometer-size particles. Combustion or electrical arc discharge is usually used as the source of energy for thermal spraying. Resulting coatings are made by the accumulation of numerous sprayed particles. The surface may not heat up significantly, allowing the coating of flammable substances.Coating quality is usually assessed by measuring its porosity, oxide content, macro and micro hardness, bond strength and surface roughness. Generally, the coating quality increases with increasing particle velocities.

Following are some of the important factors influencing thermal spray coating properties:

Powder properties

- Particle size
- Chemical composition
- Melting point
- Morphology
- Shape

Process parameters

- Spray distance
- Flame temperature
- Gas pressure
- Powder flow rate
- Surface preparation

Thermal spraying technology can be used for any of the following applications:

- Corrosion protection
- Fouling protection
- Altering thermal or electrical conductivity

- Wear control
- Repairing damaged surfaces
- Temperature/oxidation protection (thermal barrier coatings)
- Medical implants
- Production of functionally graded materials (for either of the above applications)

Different types of thermal spraying techniques are:

- Plasma spraying
- Detonation spraying
- Wire arc spraying
- Flame spraying
- High velocity oxy-fuel coating spraying (HVOF)
- Cold spraying

1.4.4.1 Plasma Spraying

The Plasma Spray Process is basically the spraying of molten or heat softened material onto a surface to provide a coating. Material in the form of powder is injected into a very high temperature plasma flame, where it is rapidly heated and accelerated to a high velocity. The hot material impacts on the substrate surface and rapidly cools forming a coating.

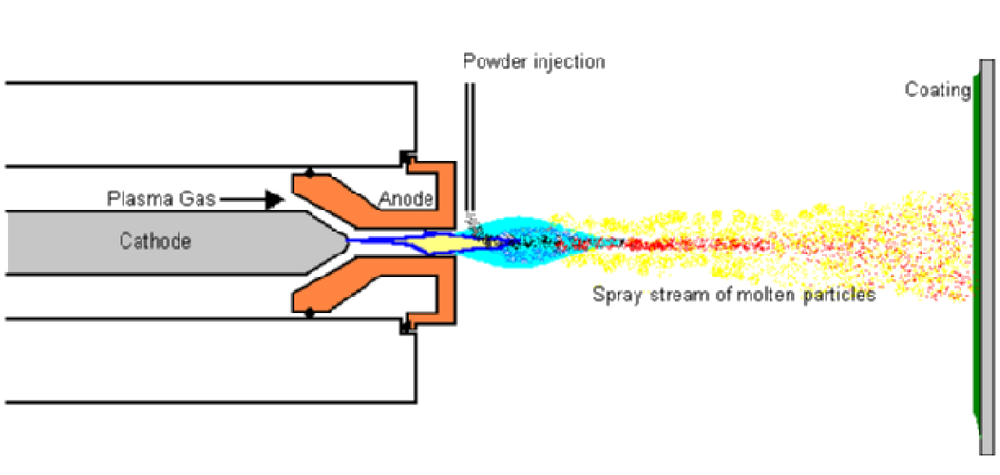

Figure 1.6 Schematic of plasma spray process

The plasma spray gun comprises a copper anode and tungsten cathode, both of which are water cooled. Plasma gas (argon, nitrogen, hydrogen, helium) flows around the cathode and through the anode which is shaped as a constricting nozzle. The plasma is initiated by a high voltage discharge which causes localised ionisation and a conductive path for a DC arc to form between cathode and anode. The resistance heating from the arc causes the gas to reach extreme temperatures dissociate and ionise to form plasma. The plasma exits the anode nozzle as a free or neutral plasma flame (plasma which does not carry electric current) which is quite different to the Plasma Transferred Arc coating process where the arc extends to the surface to be coated. When the plasma is stabilised ready for spraying the electric arc extends down the nozzle, instead of shorting out to the nearest edge of the anode nozzle. This stretching of the arc is due to a thermal pinch effect. Cold gas around the surface of the water cooled anode nozzle being electrically non-conductive constricts the plasma arc, raising its temperature and velocity. Powder is fed into the plasma flame most commonly via an external powder port mounted near the anode nozzle exit. The powder is so rapidly heated and accelerated that spray distances can be in the order of 25 to 150 mm.

The plasma spray process is most commonly used in normal atmospheric conditions and referred as APS. Some plasma spraying is conducted in protective environments using vacuum chambers normally back filled with a protective gas at low pressure; this is referred as VPS or LPPS.

Advantages:

- ✓ It can spray very high melting point materials such as refractory metals like tungsten and ceramics like zirconia unlike combustion processes.
- ✓ Plasma sprayed coatings are generally much denser, stronger and cleaner than the other thermal spray processes with the exception of HVOF
- ✓ A plasma spray coating probably accounts for the widest range of thermal spray coatings and applications and makes this process the most versatile.

Disadvantages:

- ✓ Plasma spray process has relative high cost and
- ✓ Complexity of process limits its applications.

1.4.4.2 Detonation Thermal Spraying Process

As shown in figure no 1.7, detonation gun consists of a long water cooled barrel. This barrel has valves for inlet of powder and gases. The oxygen and fuel (most commonly acetylene) is feed to this barrel through gas inlet valve. The powder is also fed to this barrel along with gases.

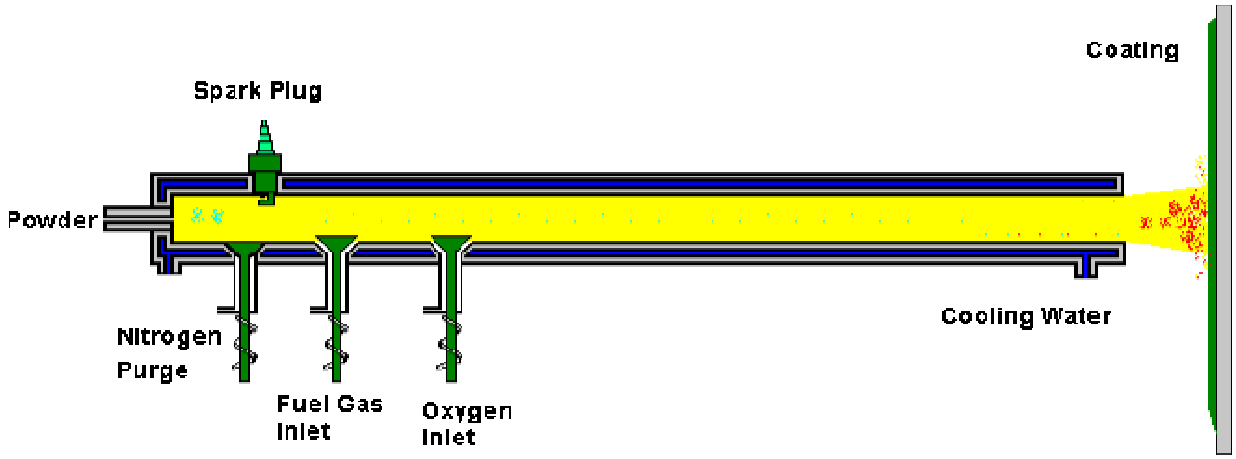

Figure 1.7 Schematic Diagram of the Detonation Thermal Spray Process

The detonation process has the following cycles.

- Injection of oxygen and fuel into long water cooled barrel.
- Injection of powder with a spark and nitrogen to prevent backfiring
- Ignition of mixture and acceleration of powder to supersonic velocity
- Purging of barrel by nitrogen.

Advantages:

- Compared to other techniques it the cheap process.
- Coating provides very good wear resistance.

1.4.4.3 Wire Arc Spray

Wire arc spray is a form of thermal spraying where two consumable metal wires are fed independently into the spray gun. These wires are then charged and an arc is generated between them. The heat from this arc melts the incoming wire, which is then entrained in air jet from the gun. This entrained molten feedstock is then deposited onto a substrate. This arc spray process carried out correctly is called a "cold process" (relative to the substrate material being coated) as the substrate temperature can be kept low during processing avoiding damage, metallurgical changes and distortion to the substrate material. This process is commonly used for metallic, heavy coatings. Theapplications for this process are anti-corrosion coatings of zinc and aluminium.

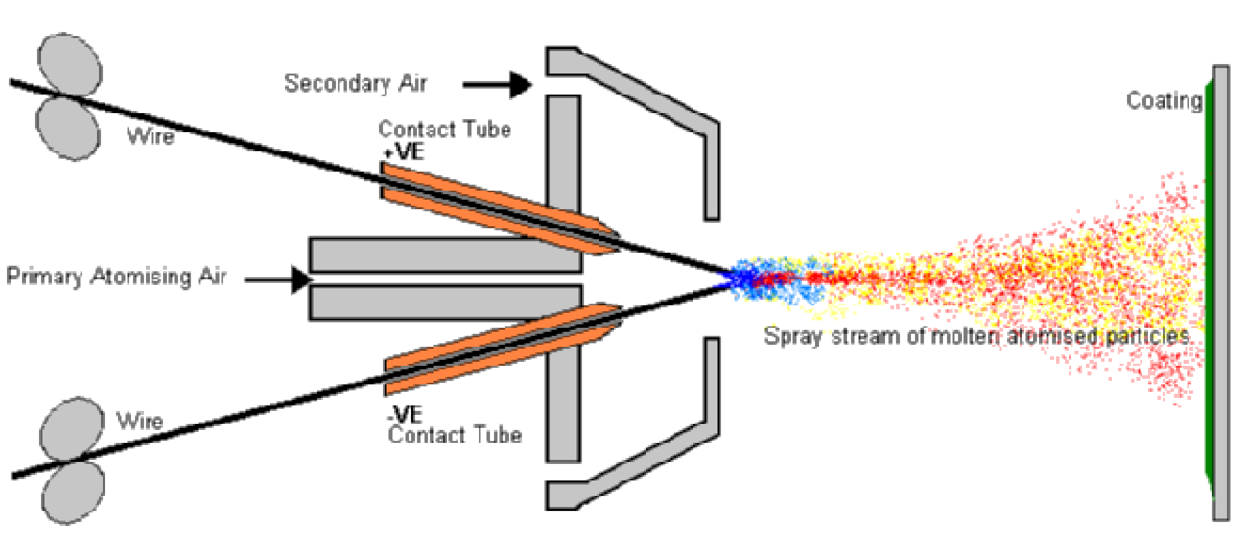

Figure 1.8 Schematic diagram of theElectric Arc Wire Thermal Spray Process

Advantages:

- ✓ Electric arc spray coatings are normally denser and stronger than their equivalent combustion spray coatings.
- ✓ Low running costs, high spray rates and high efficiency.

Disadvantages:

- ✓ Only electrically conductive wires can be sprayed.

1.4.4.4 Flame Spraying

Flame spraying is the oldest of the thermal spraying processes. In this method, the combustion of fuel gas takes place in a torch which is used to generate a hot flame. The gas and powder can be introduced axially or perpendicularly to the torch. The particles in molten state accelerate towards the work piece. The wires can also be used instead of powder. The consumable types give rise to the two process variants:

- Powder flame spraying
- Wire flame spraying

In powder flame spray, powder is fed directly into the flame by a stream of compressed air or inert gas (argon or nitrogen). . It is important that the powder is heated sufficiently as it passes through the flame. The carrier gas feeds powder into the centre of an annular combustion flame where it is heated. A second outer annular gas nozzle feeds a stream of compressed air around the combustion flame, which accelerates the spray particles towards the substrate and focuses the flame.

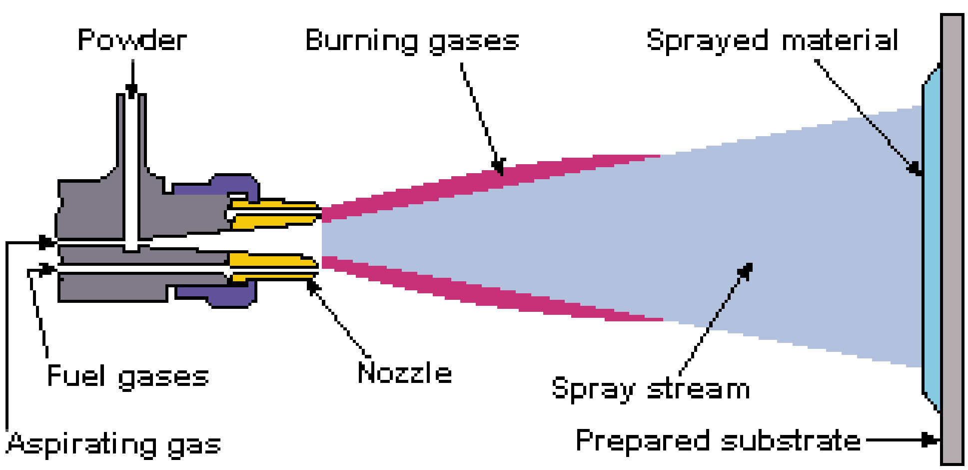

Figure 1.9 Schematic of the powder flame spray process

In the wire flame spraying process, the wire feed rate and flame settings must be balanced to produce continuous melting of the wire to give a fine particulate spray. The annular compressed air flow atomises and accelerates the particles towards the substrate.

Figure 1.10 Schematic of the wire flame spray process

Flame spray coatings are not of high quality. So this technique is used were lower cost is needed and lower quality can be tolerated.

Advantages:

- Low cost
- Used with ease for complex geometries.

Disadvantages:

- Lower quality of coatings.

1.4.4.5 High Velocity Oxygen Fuel Thermal Spray Process

During the 1980s, a class of thermal spray processes called high velocity oxy-fuel spraying was developed. A mixture of gaseous or liquid fuel and oxygen is fed into a combustion chamber, where they are ignited and combusted continuously. The resultant hot gas at a high pressure emanates through a converging–diverging nozzle and travels through a straight section. The fuels can be gases (hydrogen, methane, propane, propylene, acetylene, natural gas, etc.) or liquids (kerosene, etc.). The jet velocity at the exit of the barrel (>1000 m/s) exceeds the speed of sound. A powder feed stock is injected into the gas stream, which accelerates the powder up to 800 m/s. The stream of hot gas and powder is directed towards the surface to be coated. The powder partially melts in the stream, and deposits upon the substrate. The very high kinetic energy of particles striking the substrate surface does not require the particles to be fully molten to form high quality HVOF coatings. The resulting coating has low porosity and high bond strength.

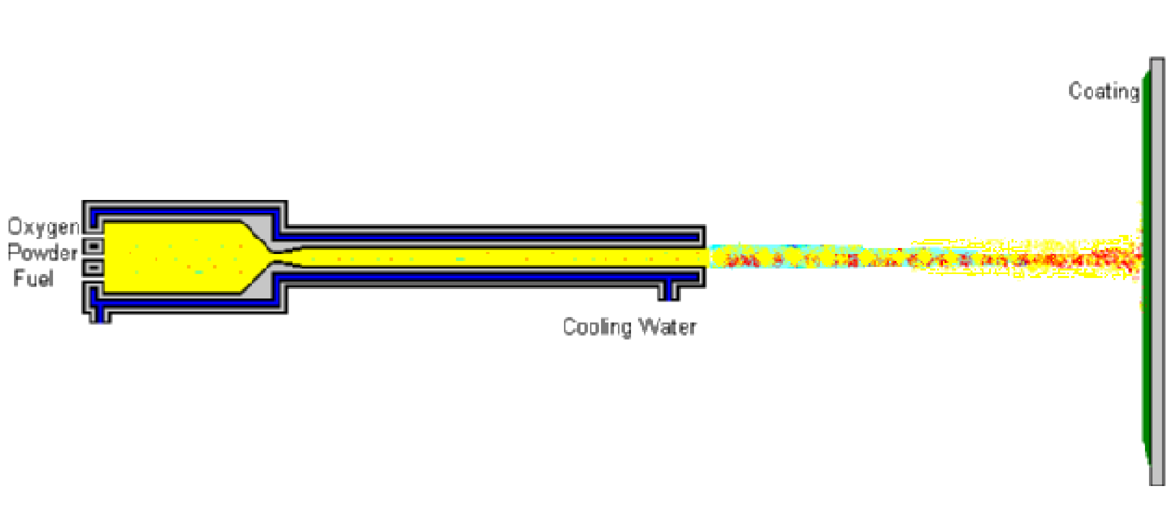

Figure 1.11 Schematic Diagram of the HVOF Process

HVOF coatings are used in applications requiring the highest density and strength not found in most other thermal spray processes. New applications, previously not suitable for thermal spray coatings are becoming viable.

Advantages:

- HVOF coatings are very dense, strong and show low residual tensile stress than coatings by other techniques.
- As the substrate surface do not require the particles to be fully molten to form high quality HVOF coatings due to high speed, This is certainly an advantage for the carbide cermet type coatings

Disadvantages:

- Very costly process.

1.4.4.6 Cold Spray Coating

DrAntolliPapyrin and colleagues at the Russian Academy of Sciences were the first to demonstrate the cold spray process in the mid-1980s.The Cold Spray or cold gas-dynamic spraying process is the next progressive step in the development of high kinetic energy coating processes. Similar in principle to the other thermal spray methods, it follows the trend of increasing particle spray velocity and reducing particle temperature as with the HVOF/HVAF processes, but to a more extreme level that it could be asked whether the process fits under the description of thermal spray.

The Cold Spray process basically uses the energy stored in high pressure compressed gas to propel fine powder particles at very high velocities (500 - 1500 m/s). Compressed gas (usually helium) is fed via a heating unit to the gun where the gas exits through a specially designed nozzle (laval type convergent-divergent nozzle mostly) at very high velocity. Compressed gas is also fed via a high pressure powder feeder to introduce powder material into the high velocity gas jet. The powder particles are accelerated and moderately heated to a certain velocity and temperature where on impact with a substrate they deform and bond to form a coating. As with the other processes a fine balance between particle size, density, temperature and velocity are important criteria to achieve the desired coating.

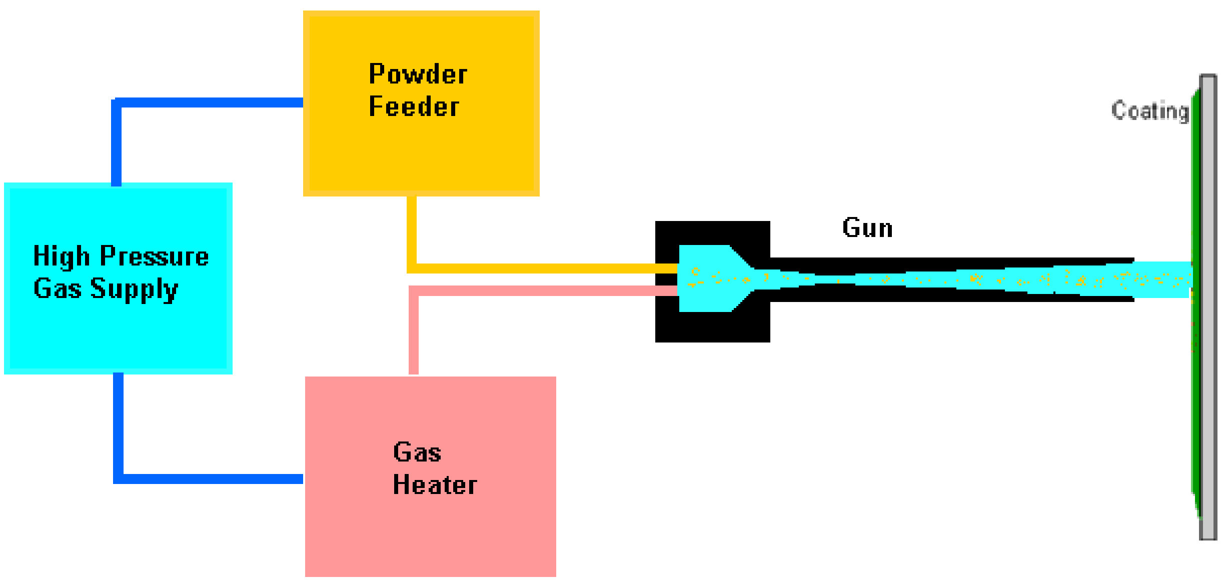

Figure 1.12 Schematic Diagram of Cold Spray Process

Advantages:

- Low temperature process, no bulk particle melting
- Very little oxidation
- High hardness, cold worked microstructure
- Eliminates solidification stresses, enables thicker coating
- Lower heat input to work piece reduces cooling requirement
- No fuel gases or extreme electrical heating required

Disadvantages:

- Hard brittle materials like ceramics cannot be sprayed without using ductile binders
- Not all substrate materials will accept coating
- High gas flows, high gas consumption.
- Helium very expensive unless recycled

1.5 MOTIVATION FOR THESIS WORK AND PROBLEM FORMULATION

Silt erosion of hydro turbines is a worldwide problem. If unattended the erosion of hydro turbines can lead to loss of turbine efficiency as high as 5-10%. Erosion is more likely to be a problem for turbine blades and nozzles in hydraulic industry which has to tolerate high speed water impingement. Selection of materials for slurry erosion resistance for hydraulic turbine is an area of considerable interest in current times. However, only few studies have been reported on the use of coatings for hydraulic turbine applications. And there is a further need to investigate the slurry erosion performance of coatings for this application.

As coatings are proved to be helpful in preventing corrosion, it will be beneficial to investigate the same for slurry erosion of hydropower plant parts. The erosion of turbine blade material i.e.

16Cr5Ni steel will be studied using jet erosion test rig. Three coating (WC-Co-Cr, $Cr_3C_2 + NiCr$ and daimlloy) have to be deposited on 16Cr5Ni steel and erosion wear will be evaluated for different operating conditions.

CHAPTER-2

LITERATURE REVIEW

Erosion may take place due to mechanical interaction between the target surface and fluid. The erosion wear has categories as solid particle erosion, liquid impingement erosion and cavitations erosion. Solid particle erosion occurs due to direct impact of solid particles (present in slurry) on the pipelines, pumps and its components. Liquid impingement erosion is associated with the continuous impact of liquid jet on the target surface and capitation erosion is defined as the repeated nucleation, growth, and violent collapse of cavities, or bubbles, in the liquid resulting in localized removal of material from the target surface.

Many Researchers have been trying to reduce the wear through various techniques but it has been difficult to find out the common cause and remedy of this problem due to its variation and dependency on large number of parameters. The parameters that affect the erosion wear in slurry transportation systems are impact velocity, impact angle, size and shape of solid particle impacting on target surface, concentration of slurry, material of target surface, and particle size distribution in the slurry, slurry viscosity and combination of all of these.

NeilsonandGilchrist (1968)have studied the total wear at normal impact angle. They assumed that the total wear to be contributed by only deformation wears. They evaluated deformation factor (ε) as given below:

$$\varepsilon = \frac{W_d}{\frac{1}{2} M \left(V \, Sin\theta - k \right)^2} \qquad \text{..} \qquad (2.1)$$

where W_d is deformation wear at normal impact condition, 'M is the total mass of impacting particles, 'V' is velocity of particle, θ is impact angle and *k* is the normal component of particle impact velocity needed to initiate the erosion which is generally neglected, considering very small compared to the impact velocity

J. B Zu et al. (1990) had designed a new jet impingement slurry erosion tester. It consists of a three phase centrifugal pump and slurry flows in a closed loop. The impact angle and velocity can be varied according to requirement. They also determine the effects of degradation of erodent particles arise from their recirculation. The experiment was carried for 20% concentration of sand slurry. They observed a small rise in erosion wear for first 200 min. thereafter erosion rate remains almost constant for next 900 min. A slow decline, by maximum of about 20% in erosion rate was observed after 2300 min. which was due to degradation of erodent particles.

Lynn et al.(1991) have studiedeffectof slurry particle size on slurry erosion using a pot tester at a constant velocity of 18.7 m/s on steel specimen. Slurry was prepared by mixing 1.2% by weight of silica carbide in oil for different eqisized diameter ranging from 20µ to 500µ. They conclude that for particles sizes greater than about 100µ the erosion rate was proportional to the Kinetic energy dissipated by particles during impact but for particles size less than 100µ other metal removal mechanism become increasingly significant. Both collision efficiency and impact velocity of particles decreased with decreasing particles size.

.**Lin and Shao(1991)** studied the effect of velocity on erosion wear in a newly designed erosion tester using eqisized sand-water slurry. The velocity was varied between 10 m/s and 70 m/s and impact angles between 15ºand 90º. Four specimens (pure aluminium, 1020 steel, high chromium and cast iron) were tested at a constant concentration of C_w = 5%. They found that the velocity exponent increase with increasing impingement angle and decreased with increasing hardness. Velocity exponent in the ranges of 1.87-2.48 were observed for different impingement angles and different materials. At 90º impingement angle, the index of velocity for erosion wear for aluminium was 2.48 where for the chromium it was 2.17. This implies that with increase in hardness of the test materials, the exponent of velocity decreases.

Singh et al. (1991) found that both 304 and 316 stainless steels have the same rate of wear when impinged with an air jet containing SiC particles that were 160 microns in diameter and angular shapes. In both metals have wear rate fastest when the impingement angle was at 30° and it was the slowest at 90°.This information is very useful when designing a test because it indicates where attention must be directed to evaluate the maximum wear locations. Wear measurement must not be concentrated only at a section of a flow loop where the flow makes an abrupt 90° change.

Miller and Miller (1993) have conducted an experiment to check the effect of slurry concentration on erosion wear. They found that erosion rate increases rapidly as the slurry concentration increases to 10 %by weight , but after 20 %by weight the erosion rate dependence is relatively unaffected by further increases in concentration.

Rajatgupta et al. (1995) studied the effect of velocity, concentration and particle size on erosion wear. The experiment was performed by pot tester for two pipe materials, namely brass and mild steel. They evaluated that for a given concentration, erosion wear increases with increase in velocity and for a given velocity, erosion wear also increases with increase in concentration but this increase is comparatively much smaller. They also concluded that erosion wear decreases with decrease in erodent particle size.

Krause et al. (1996) using test rig carried a test with 13Cr4Ni steel. A natural river sand of various grain sizes was used as slurry. The test rig was designed to simulate the flow conditions in a turbine. They concluded that the erosion rate is the function of velocity, slurry concentration and grain size of slurry. They also found that grain size of range 40-70μm showed maximum abrasion.

Yoshiro Iwai and Kazuyuki Nambu (1997) studied the effect of concentration, velocity and impact angle on pump lining material on jet erosion tester. They formulated an empirical relation of predict the wear.

$wear \propto (v - v_o)^n C^m (d - d_o)^3$ .... (2.2)

Where Vo and m are dependent on the particle size but n is number of particles.

$v_o =$ Critical velocity

$d_o =$ Critical diameter of solid particles

C^m= Concentration

They also evaluated that rubber owes its high slurry wear resistance than other two pump lining materials (fluid elastomer, polyurethane).

R Dasgupta et al.(1998) evaluated the effect of sand slurry concentration on steel using DUCOM made TR 41 erosion tester. They also varied the rotational speed and traverse distance during the test. They concluded that increase in the concentration of sand reduces the erosion rate. They also concluded that erosion rate deteriorates with rotational speed. They were fail to clearly show the effect of traverse distance on erosion wear.

S V Joshi et al.(1998) studied the erosion resistance of WC-12Co, $Al_2O_3 and Cr_2C_2$+25% NiCr deposited on mild steel. They found that WC-12Co showed maximum erosion resistance followed by $Al_2O_3 and Cr_2C_2$+25% NiCr respectively. The influence of wear intensity was also studied and it was observed increase in wear intensity, the wear resistance decreases and thus examination of wear mode and intensity is needed to be evaluated well before applying the coatings.

Gandhi et al. (1999) measured the erosion rate of steel plating by a jet of sand and water. The particles ranged from 200 to 900 microns and the solids concentration from 20 to 40 % by weight. Using velocities from 3 to 8 m/s they evaluated that the erosion rate = f(velocity$^{2.6}$). When changing the material of the eroding surface the exponent of particle velocity also changes.

Xie et al. (1999) determined that for very dilute slurries, where the solids concentration is less than 1%by volume, or when the particle-to-particle distance is greater than 20 times a particle diameter, the effect of the solids concentration can be neglected, because the particles do not interfere with each other.

Hawthorne et al (1999) using jet erosion tester performed an experiment to evaluate erosion wear on WC and Cr_2C_3 (HVOF) coatings. At the velocity of 15m/s the coatings were subjected to slurry of alumina particles in water at two different impact angles of 20° and 90°. By varying the grain size of slurry they concluded that WC shows better result for grain size of 150μm and <150 for both the angles. For smaller particle Cr_2C_3 shows better performance.

RupaDasgupta et al.(2000) studied the erosion behavior of high carbon steel (.65% C) in coal and bottom fly ash. The test was performed with concentration of 30% by weight using DUCOM slurry abrasion test apparatus. They evaluated that bottom fly ash slurry caused higher material loss than coal slurry because bottom ash slurry consists of larger quantity of harder mineral constituents. They also evaluated that the wear loss of the specimens increased with traversal distance.

Abbade and Crnkovic(2000) found that changing the surface hardness did not significantly affect the wear rate. They used a low carbon, niobium-titanium, steel (API 5L X65) in annealed and heat treated conditions, which doubled the metal's yield and tensile strengths. The test was performed with jet erosion tester at angles of $30°$ and $90°$. Slurry was made of water that contained 3.5% by weight of sand with particles size from 150 to 300 microns. Both the heat-treated and non-heated surfaces displayed the same wear rate, for the same particle direction

Walker (2001) compares the wear rate of the white cast iron with rubber material. He found that both material show excellent similarities in wear rate trend with particle size but rubber show lower wear rate than the metal for equivalent particle size < 700µm. This is because the rubber surface can absorb smaller particle impact energy without significant cutting tearing.

Factor et al. (2002)evaluated the erosion wear using solid particles in He gas of Wc-17Co and $Cr_3C_2 + 25NiCr$ coatings on steel alloy using Sic as erodent. They evaluated that coating helps in reducing the erosion wear. At an angle of $90°$ Wc-17Co shows the better result but a low impact angles $Cr_3C_2 + 25NiCr$ was better.

Chen and Li(2003) simulate the effect of shape of slurry particles using computer model (Micro-scale dynamic model, MSDM). They found the difference in erosion rate of three basic shapes (Triangular, square and circle) by keeping all other parameters constant. The triangular shaped particles have the maximum erosion rate and circular particles show the lowest erosion rate.

Gandhi and Borse(2004) defined the nominal size of multi-sized particulate slurry. They define that the effective particle size for narrow-size particulate slurries can be taken as the mean size whereas the weighted mass particle size seems to be a better choice for multi-sized particulate slurries. They also evaluated the effect of presence of finer particles (<75_m) in slurry. By adding finer particles to both type of slurries test was conducted on grey cast iron. Velocity and impact angle was kept constant as 3.62m/s and 30°respectivelty. They found the reductions in erosion wear due to addition of fine particles decreases with increase in the concentration of coarse size particles.

Neville et al. (2005) studied the erosion-corrosion behavior of WC-Metal Matrix Composites(EFM, EFW, EGC, EGG). The materials were eroded by two sizes of silica sand with stream velocities of 10 and 17 m/s at 65 ◦C. Test was conducted by varying the concentration. They evaluated that WC grain size fractions has very little effect on wear. They also concluded that the erosion–corrosion rate is strongly dependent upon erodent size, impinging velocity and solid loading.

Mishra et al. (2005) evaluated the erosion wear performance of Ni-Al powder taken in ration of 3:1 by weight. APS method of thermal spray was used for coating. Test was conducted at different angles and standoff distance. They found that the maximum erosion was in between 30°-40° impact angles. They also found the relationship between stand of distance and erosion wear. With increase in stand of distance, erosion rate decreases i.e. inversely proportional.

BS Mann et al. (2006) compared erosion behavior of WC10Co4Cr, Armcore 'M', Stellite 6 and 12 HVOF coatings, TiAlN PVD coatings. Impact angle of 60° and velocity of 20m/s was kept constant for all experiments. Mineral sand was used as solid particles of slurry. They concluded that WC10Co4Cr HVOF coatings show best performance against slurry erosion. They also evaluated the corrosion performance and found that WC10Co4Cr HVOF coating corroded significantly. WC10Co4Cr HVOF coatings have very good erosion resistance but not corrosion resistance.

M.A. Al-Bukhaiti et al. (2007) studied the influence of impingement angle on erosion mechanisms of 1017 steel and high-Cr white cast iron using a slurry whirling-arm test rig. They found that by changing the impact angle the mechanism of erosion also changes. At low impingement angles, ploughing and micro cutting were the predominant erosion mechanisms of material removal. Whereas at high impingement angles plastic indentation was the main erosion mechanisms.

A Toro et al. (2007) compared the erosion wear of coated and uncoated stainless steel used for hydraulic machinery. The slurry was composed of distilled water and quartz sand particles with an average diameter between 212 and 300 _m and the solids content was 10 wt% in all the tests. The mean impact velocity of the slurry was 5.5 m/s. It has been observed that the coated surfaces showed higher erosion resistance than the uncoated stainless steels. Toro also compared the wear of AISI 304 stainless steel by applying E-C29123 (WC/Co in Fe–Cr–Ni matrix) coating and T 35 MXC (Al2O3-reinforced high-carbon steel) coating. They evaluated that the E-C 29123 coating onto AISI 304 stainless steel reported the better slurry erosion resistance of the studied material than T 35 MXC.

T. Manisekaran et al. (2007) studied the effect of surface treatment on erosion rate of 13Cr 4Ni steel at various angles of impingement. Pulsed plasma nitriding and laser hardening techniques were used for surface hardening. The results have shown that Laser hardening process has good performance at all angles of impingement due to martensitic transformation of retained austenite. They also concluded that by increasing erodent particle size erosion rate also increases

Berget et al. (2007) evaluated the effect of grain size distribution on erosion wear. WC-Co-Cr powder was coated on to 22Cr5Ni steel. Three different ranges of grain size(15-45, 25-38 and 36-45 μm) were examined with jet erosion tester. Silica particles of 250 μm at 0.25% concentration, impinges on specimen at velocity of 14 and 23m/s. They evaluated that with increase in grain size of powder erosion reduced substantially. Erosion wear of 36-45μm is almost 1/4th as compared to 15-45μm.

B K Gandhi et al.(2008) evaluated the erosion wear of ductile material under normal impact conditions. By keeping solid concentration as 10 % wt, velocity as 3m/s and particle size as 550_m test were conducted on seven different materials. Those were aluminium alloy (AA6063), copper, brass, mild steel, AISI 304L stainless steel, AISI 316L stainless steel, and turbine blade steel. Solid particles of slurry were mixture of quartz, alumina and silicon carbide. They evaluated that erosion of target material is dependent on ratio of hardness of solid particles to hardness of target material and independent of hardness of target material and hardness of slurry particles. By varying particle size, concentration and velocities they formulated an empirical formula for erosion rate at normal condition:

$$E_{D90} = 6.62 \times 10^{-14} \times K_{(H_p/H_T)} V^{2.02} \times d^{1.62} C_w^{-0.285} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2.3)$$

Where V= velocity of impacting particle

d= particle size

$C_{w=}$Concentration by wt

$k_{(H_{P/H_T})}$= constant, value depends on hardness of target material and of particles.

S.C. Mishra et al. (2009) studied all the parameters affecting the erosion wear using jet erosion tester on fly ash-quartz coating. By varying different parameters they evaluated that impact angle is the most significant factor influencing the erosion wear of fly ash-quartz coating. They also evaluated that maximum erosion takes place at impact angle of 90°.

Y. Iwai et al. (2009) evaluated the erosion resistance of TiC and TiN coatings using micro slurry jet erosion (MSE).CVD (chemical vapor deposition) technique was used for coating. Slurry containing 1.2μm alumina particles was impacted at high velocity perpendicular to CVD TiN and TiC coatings deposited on cemented carbide. They evaluated that TiC layer have about two times higher wear resistance than the TiN layer. They also studied the erosion wear of TiC/TiN (TiN on top of TiC). They concluded that the wear depth of the TiN layer increased linearly until the TiC layer was reached. There after the wear occurred at a lower rate but tended to increase towards the TiC/substrate interlayer.The wear rate was constant within the individual TiN and TiC layers, but changed near the interfaces.

J.F. Santa et al. (2009) compared the erosion and corrosion resistance of various thermal spray coatings on martensitic stainless steel. Nickel, chromium oxide and tungsten carbide coating were applied by oxy fuel powder whereas chromium and tungsten carbide coating were applied by HVOF. A modified centrifugal pump was used to evaluate the erosion performance. They found that thermal spray coating has more erosion resistance as compared to bare steel. They also found that coatings do not help in preventing cavitations, in fact shows poorer performance than bare steel

B K Gandhi et al.(2009) studied the effect of particle size on erosion wear of aluminum alloy (AA6063) using pot tester. Quartz particle were used as slurry of eight different sizes varying between 37.5 and 655_m. keeping the concentration of 20% by weight and velocity as 3m/s experiment was conducted. They found that the erosion wear increases with increase in mean particle size.

S.L.Liu et al. (2010) studied the influence of nano-WC–12Co powder addition in WC–10Co–4Cr AC-HVAF (high velocity air fuel) sprayed coatings on wear and erosion behavior. Slurry erosion tests were performed on a jet erosion tester. The slurry consisted of the quartz sand of −400 to+625 mesh in water. The slurry passes through a nozzle of diameter 6mm, providing a jet velocity of 46 m/s at an angle of 30◦. They concluded that by addition of nano-WC–12Co powder erosion wear resistance increases. They also concluded that by addition of nano-WC–12Co powder hardness also increases.

Huang et al.(2010)developed a comprehensive phenomenological model for erosion of material in slurry pipeline flow based on the turbulent flow theory and his previous model. This model captures the effects of particle shape, particle size, slurry mean velocity, pipe diameter, fluid viscosity and the properties of target material.This model shows that erosion rate has a power-law relation with particle shape and size, slurry mean velocity, liquid viscosity and pipe diameter. Huang formulated the equation written below:

$$ER = b^{1.375} * c^{*}\rho_p^{1.1875} d^{0.5} u_o^{3.375} \gamma^{0.516} R_{ed}^{-0.6875m} \quad \text{.......................................} \qquad (2.4)$$

Where b and c* are constants. There value depends on properties of target material.

$\rho_{p=}$Particle density

d= Pipe diameter

$u_{o=}$Slurry mean velocity

$R_{ed=}$Reynolds Number (All in SI units)

CHAPTER-3

EXPERIMENTAION

Jet type of test rig selected for experimental investigation of erosion is at Baba Banda Singh Bahadhur Engineering College, fatehgarhSahib.

3.1 DESCREPTION OF TESTING APPARATUS

The test rig shown consists of a centrifugal pump, conical tank, nozzle, specimen holder, valves and flow meter. Centrifugal pump driven by 7.5 HP, 1400 rpm electric motor has a capacity of max pressure 13.5 bar at a discharge of 240L/min. Slurry available in conical tank as can be seen in figure3.1 is sucked through a 100mm GI pipe with help of pump and delivered to the nozzle through 25 mm pipe having control valves and electromagnetic flow meter located upstream. Slurry is re-circulated during test. During test the temperature of slurry increase to a certain level and thereafter remains constant, which is due to mechanical action of pump. The flow rate of the slurry is controlled with help of main valve and bypass regulator valve between delivery side and nozzle. The rectangular tapered tank having 650x650 mm at top which converges to 100x100 mm at the bottom through a length of 700mm was used to store the slurry. A mesh is provided in the bottom of the tank to avoid the object from falling into the tank and get struck inside the pipeline.

Slurry flowing through the pump at high pressure is converted into high velocity stream while passing through the converging section of the nozzle which is 125mm long and having diameter of 8 mm. the standoff distance between the nozzle and specimen can be varied from 25mm to 90mm. After striking the specimen slurry falls back into the tank, as the holder is located on the top of tank enclosed in a casing made of steel angle and fitted with fiber sheet, to facilitate the removal and clamping of the specimen. The electronic magnetic flow meter (Elmag-200M) arranged as shown in figure 3.1 in between control valves and nozzle is equipped with digital display and contains PTEF coated liner through which the slurry flows and discharge is calculated, when a conductive fluid passes through magnetic field (applied) a voltage is induced in an electrically conductive body which is proportional to the mean flow velocity according to Faraday’s law of induction..

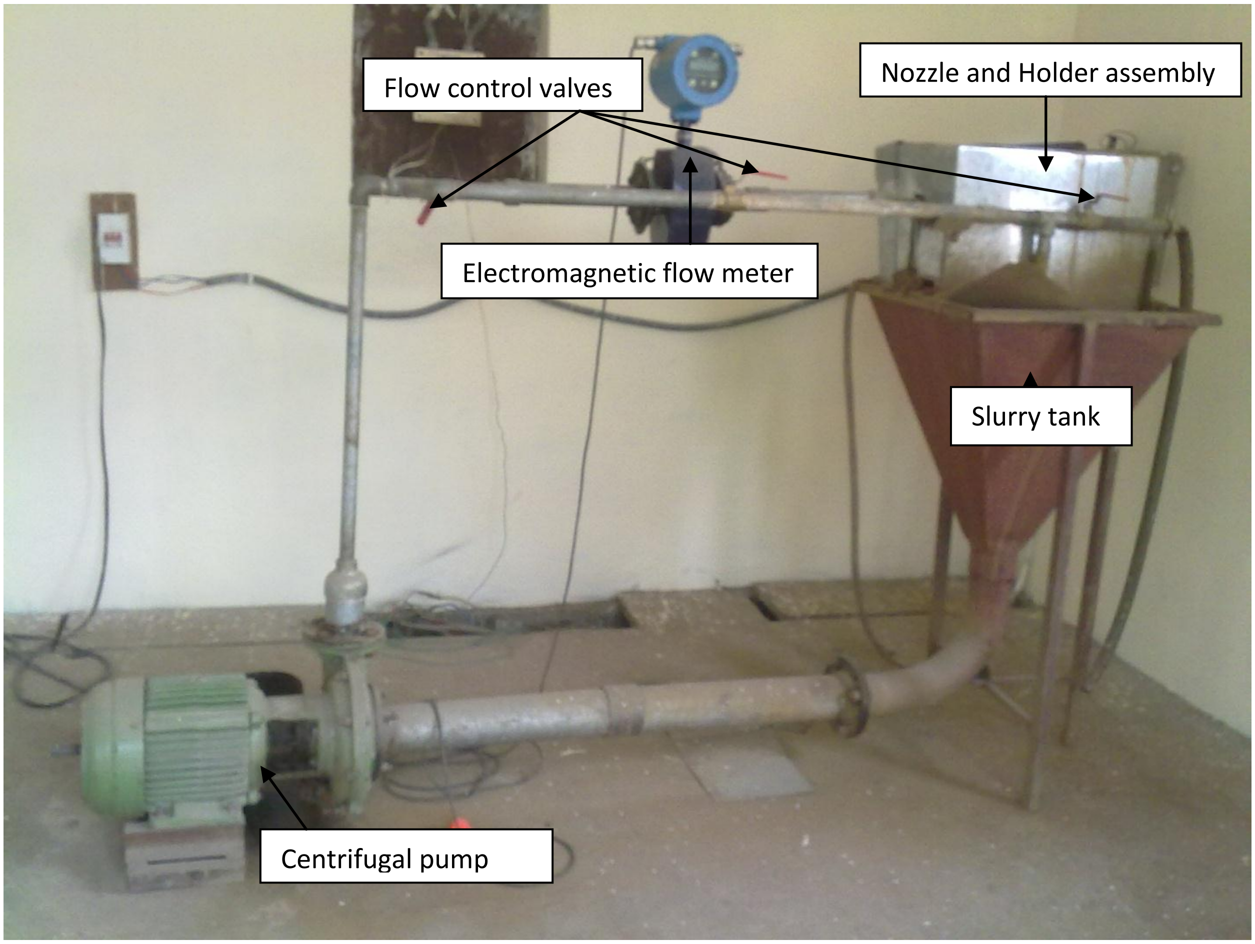

Figure 3.1 Jet erosion tester

Figure 3.2 (a) View of Nozzle holder assembly

Figure 3.2 (b) Closer view. Specimen fixed in holder and nozzle

3.1.1 WORKING OF JET EROSION TESTER

In jet erosion, testing a high velocity jet strikes a flat specimen at some adjustable angle. In jet erosion tests, the amount of material removed is determined by the weight loss. The material which accumulates on the specimen surface interferes with the incoming particle. The weight loss of the specimen corresponds to the average erosion over the surface.

Jet erosion tester has been developed to investigate the effect of different parameters particularly the impact angle and velocity under controlled environment. In jet erosion tester, a circular jet of solid–liquid mixture strikes at the wear specimen fixed in a fixture, which can be oriented at any angle with respect to the former. Generally a pump is used to drive water at high pressure

3.2 PREPRATION OF SAMPLES

The steel mostly used in modern turbine industry i.e. 16Cr5Ni is to be used for testing purpose. The dimension of the samples is to be kept as$40 \times 45 \times 5mm$. Power hacksaw was used to cut the pieces from bar. The surface of each sample was finished by surface grinder. As per the requirement the coating is to be done on the sample. The high velocity oxy fuel (HVOF) thermal spray technique has been used for coating. Both sides of the samples were used for testing for coated and noncoated materials.

The coating of powder over the samples is done with HVOF technique, from Metalizing Equipmentscompany pvt ltd, Jodhpur. Before applying the coatings, the samples were grit blasted with alumina grit using abrasive blasting machine (shown in figure 3.3). Blasting of samples is necessary before applying the coating so as to supplement the adhesion of the coatings to the surface of sample.

Figure 3.3 Abrasive blasting machine

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3.3DESCRIPTION AND WORKING OF HVOF APPARATUS

In HVOF process the fuel (Gas/Liquid) is introduced into the combustion chamber along with oxygen. The fuel oxygen mixture is burnt and exhausted through nozzle. The powder to be coated is supplied along with this superheated high velocity stream. The powder become in molten state and gets coated to surface. The HVOF apparatus used for coating to samples, at Metalizing Equipment is shown in figure 3.4.In this process LPG was used as fuel (Gas). The nitrogen gas was used as a carrier gas. Carrier gas is used to circulate/supply the powder along with superheated, high velocity stream. A very high temperature of 3000+℃ can be achieved. A very high velocity of about 800m/s is used during the process. Still higher upto 1200m/s was achievable. The indicator in the control panel indicates the flow of fuel oxygen and carrier gas. The powder was filled in the black box just below the indicators and above stop/start button.

Figure 3.4 HVOF coating apparatus

3.4TEST PROCEDURE

The jet erosion tester used for this work is not automated. Most of the activities in the erosion test are manual. During experiments all the observations are recorded manually. Brief sequence of the test procedure is as follows:

1. Cleaning the specimen properly
2. Drying, if required

3. Weighing the specimen (initial weight)
4. Clamp the specimen in test rig
5. Setting the holder at required angle
6. Weight the required sand as per concentration of slurry
7. Mixing the proper amount of water and sand in tank
8. Start the pump
9. Adjust the flow rate to obtain desired value of velocity
10. Running the test for required time interval
11. Removing the specimen from rig
12. Cleaning and drying the specimen
13. Weighing the specimen after erosion to measure the mass loss
14. Repeat the steps from 4 to 13 as per requirement

CHAPTER 4

STUDY OF PROPERTIES OF MATERIAL

4.1 BENCH SCALE TEST

The sand used to erosion test was collected from the NapthaJhakri Power house, H.P. The sample of sand was collected from the water which was coming out of draft tubes of turbine.Various bench scale tests were carried out on sand collected to determine the specific gravity, particle size distribution (PSD) of the solid materials. The pH value & static settling characteristics of sand slurry was also determined in the laboratory at IIT Roorkee. A brief description of these tests is presented here.

4.1.1 PARTICLE SIZE DISTRIBUTION

The variation in the size of the particles in the solid sample and the percentage of particles present in different pre-selected size ranges are determined to establish the particle size distribution (PSD). Two methods namely sieve analysis and hydrometer analysis, can be employed to get this distribution. In the present study a known weight of sample of solid particles is taken and washed over a B.S. 200 mesh (75 mm). Particulate materials are dried in an oven. The dried material is sieved through a set of standard sieves. Special care is taken to ensure that the sample is properly dried. The sample retained on each sieve is collected and the percentage retained on each sieve is calculated using the standard procedure.

4.1.2. SPECIFIC GRAVITY

In the present study, the specific gravity of solid particles is determined using fixed volume bottle. In this method first take 50 ml fix volume bottle and clean it thoroughly, keep it in the oven in order to remove moisture from bottle. After 2 hours, take out the bottle from an oven and allow it to cool down, and then take the weight of bottle (W_b). After weight put some solids (over dried) about 30 grams in it and weight it again and note down this weight (W_{bs}). After this slowly pour water (distilled) in the bottle so that no air is entrapped in it and shake it well, and keep on pouring the water. Shake it well each time till all the solid get wet. Fill $3/4^{th}$ of bottle with water and put the thumb on the mouth of the bottle and shake it well for 5 minutes. Keep it for at least 2 Hours, so that air bubbles get out from the bottle. Then fill the bottle of water and cork it. Clean it with cloth/tissue paper and weight it. Note down the weight (W_{bsw}). Now remove the solids from the bottle and clean it, Thoroughly, Dry it and fill it with distilled water. Note down the weight (W_{bw}). Calculate the specific gravity of solids as given below.

Specific Gravity of solids= $(W_{bs}-W_b)/ \{W_{bw}-W_{bsw}+(W_{bs}-W_b)\}$

Where, W_b = Weight of beaker

W_{bs} = Weight of beaker and solid

W_{bw} = Wight of beaker and water

W_{bsw} = weight of beaker, solid and water

4.1.3 STATIC SETTLED CONCENTRATION

The static settled concentration is an important parameter as it decides the highest limit of solid concentration, which can be achieved by gravitational settling. The static settled concentration depends on a large number of parameters like specific gravity, shape and size distribution of solids, density and viscosity, of carrier fluid etc. It is well accepted that the optimum concentration for solids transportation is around 5 to 10% lower than the static settled value.

In the present study, the static settled concentration has been determined by preparing a slurry sample of intermediate concentration i.e. 20% (by weight) and allowing it to settle in a graduated measuring jar till the level of the solids become constant. This value of solid concentration in the settled portion of slurry is the static settled concentration. The slurry level at regular intervals of time was also recorded during the process of settling of the slurry to determine the setting rate of the slurry.

4.1.4 pHVALUE

A pH meter was used for measurement of the pH value of the slurry of any given solid concentration. The electrode of the meter was first moistened with tap water and then calibrated with a buffer solution of a known pH value. It is cleaned by rinsing vigorously with distilled water and then immersed in the slurry sample whose pH value was to be determined. The pH suspension was read on the digital display unit when equilibrium value was reached. The pH value of sand slurry of 3% which is used during experimentation is 7.67

4.2 PHYSICAL PROPERTIES OF SAND

Physical properties of sand are given. The specific gravity of sand was determined as 1.6. Particle size distribution of sand given in Table 4.2 shows that the largest particle is 350µm and only 3% particles are finer than 75µm. Figure. 4.2 shows the Particle size distribution ofsand. Fig. 4.3shows the static settled of sand is 56.2% by weight.

(1) Specific gravity of Sand: 1.6, particle size d_{50} = 230 µm, d_{wn} = 162.139 µm

(2) Rheological Properties of bottom ash at temperature 26°C

(3) Static settled concentration of slurry = 56.2% with Initial concentration= 20%(by weight)

(4) pH value of sand slurry of 3% concentration is 7.67

(5) Particle size distribution

Table 4.1 Particle size distribution

Sr. No.	Particle size, µ	% finer
1	355	100
2	300	97
3	250	91
4	212	87
5	180	83
6	150	61

7	125	31
8	90	6
9	75	2

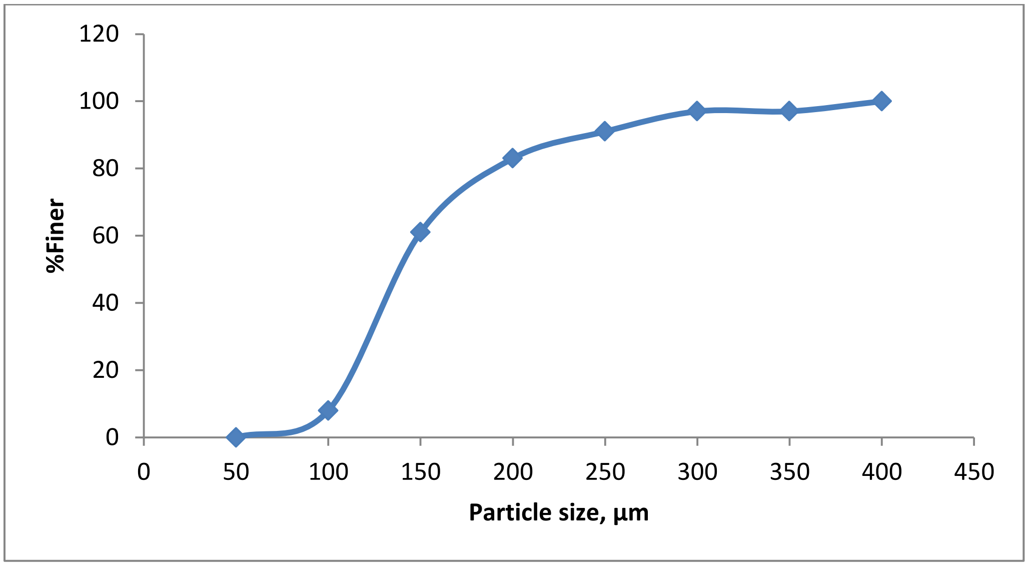

Figure 4.1 PSD of sand

Table 4.2 Settling concentration of sand

S No	Time Span	Volume Settled (V_t) ml	M_w=(V_t-V_s)1000	Conc. (C_w)
1	10 Sec	490	0.428	18.95
2	20	490	.428	18.95
3	30	480	.417	19.3
4	40	480	.417	19.3
5	50	475	.412	19.5
6	60	470	.407	19.7
7	2 min	460	.397	20.1
8	3	455	.39	20.3
9	4	440	.378	20.9

10	5	415	.35	22.2
11	15	390	.328	23.36
12	30	200	.138	42
13	1 hr	150	.088	53.2
14	2	140	.078	56.2
15	3	140	.078	56.2
16	4	140	.078	56.2
17	9	140	.078	56.2

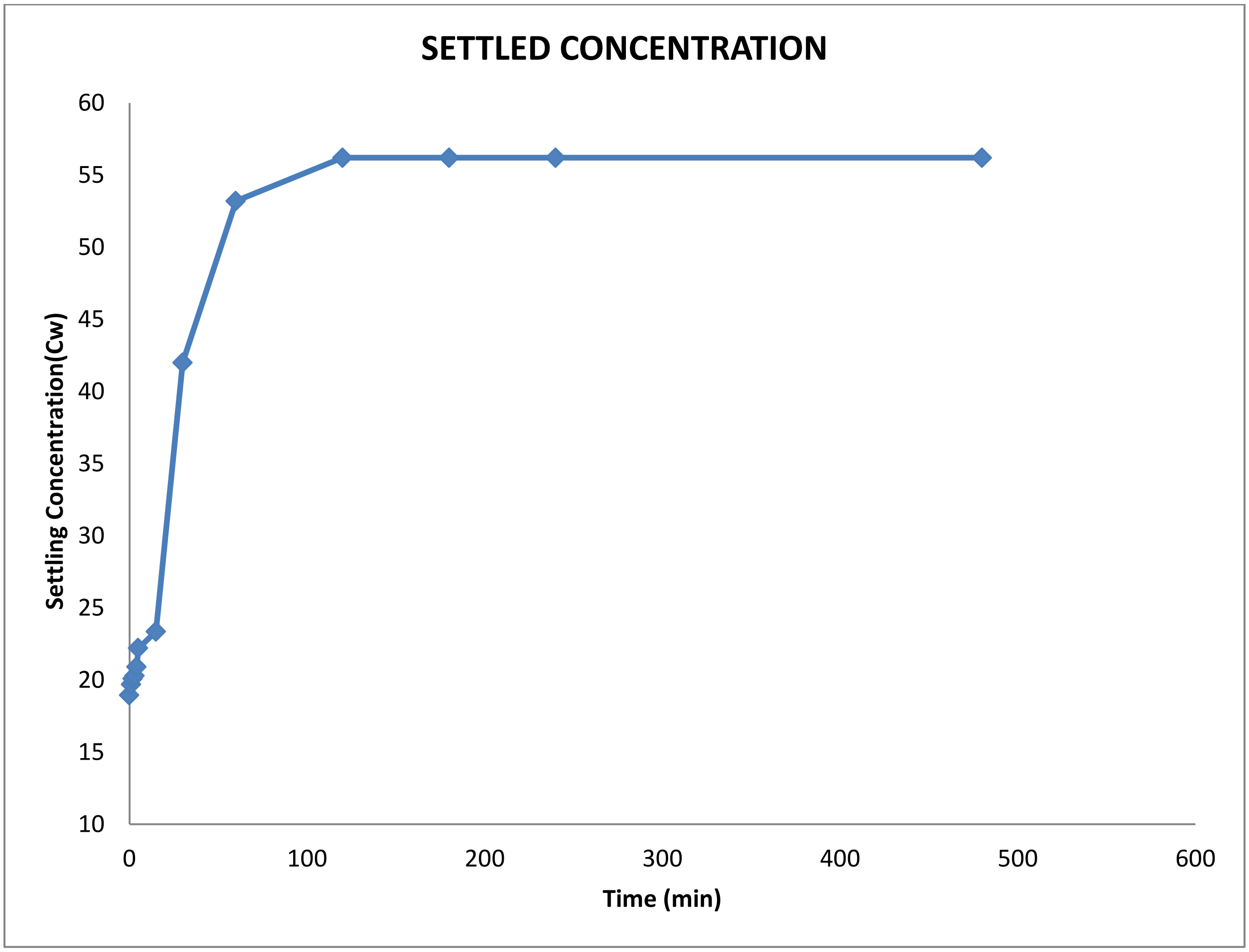

Figure 4.2Settled concentration curve of sand

4.3 SCANNING ELECTRON MICROSCOPY OF SAND

A scanning electron microscope (SEM) is a type of electron microscope that images a sample by scanning it with a high-energy beam of electrons. The electrons interact with the atoms that make up the sample producing signals that contain information about the sample's surface topography, composition, and other properties such as electrical conductivity. The sample of sand used for erosion purpose was examined with help of scanning electron microscope with aim to visualize its shape and size. The result of SEM is shown in figure 3.1.

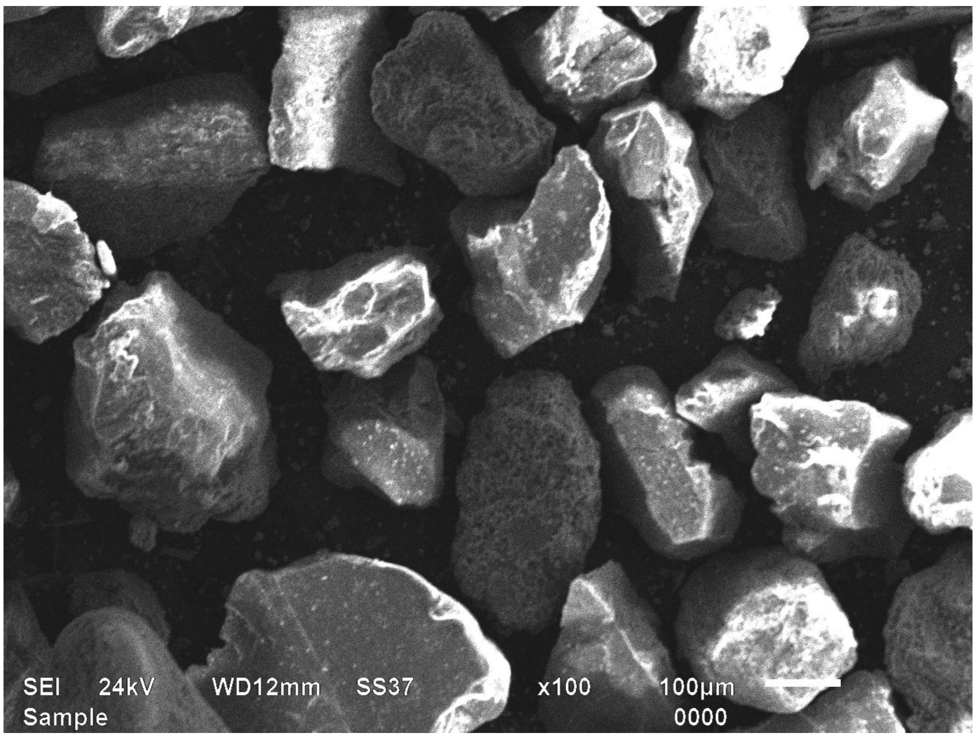

Figure 4.3 SEM analysis of sand

4.4 PROPERTIES OF MATERIAL

Before analyzing the erosion wear of 16/5 steel (most commonly used in turbine materials, as shown in table no 1.1) it is important to study the various properties of material. The base material is coated with three powders to enhance it surface properties. HVOF thermal spray coating technique is used for coating. The various coatings are WC-Co-Cr, $Cr_2C_3 + NiCr$ and diamalloy. The cast bars of base material were cut on by power hacksaw of 6mm thickness. Then the samples were grinded to 5mm thickness on both the faces by surface grinder. Properties of material to be studied are:

- Chemical composition
- Microhardness
- Microstructure

4.4.1 CHEMICAL COMPOSITION

The detailed composition of material used ie 16/5 steel is checked with help of spectrometer (shown in figure 4.5). Spectrometer is used to check the detail composition of ferrous materials.

Figure 4.4 Spectrometer

Table 4.3 Chemistry of material and coatings

Material	% composition
16/5 steel	0.1%C, 15.6% Cr, 5.7% Ni
WC-Co-Cr Coating	86WC-10Co-4Cr
Cr_3C_2+NiCr	75Cr_3C_2,25NiCr
Diamlloy (4454)	CoNiCrAlY

Sample: aseem2

Element	Burn 1	Burn 2	Burn 3	Burn 4	Burn 5	Burn 6	Burn 7	Burn 8	Burn 9	Burn 10	Burn 11	Average
Fe %	76.7	76.6										76.7
C %	0.0505	0.0277										0.0391
Si %	0.267	0.261										0.264
Mn %	0.642	0.638										0.640
P %	< 0.0030	< 0.0030										< 0.0030
S %	< 0.0050	< 0.0050										< 0.0050
Cr %	15.5	15.8										15.6
Mo %	0.664	0.651										0.657
Ni %	5.81	5.69										5.75
Al %	< 0.0010	< 0.0010										< 0.0010
Co %	0.0674	0.0692										0.0683
Cu %	0.135	0.140										0.138
Nb %	< 0.0020	< 0.0020										< 0.0020
Ti %	< 0.0020	< 0.0020										< 0.0020
V %	0.0328	0.0395										0.0361
W %	< 0.0200	< 0.0200										< 0.0200

Figure 4.5 Composition of 16/5 steel as shown by spectrometer

4.4.2 MICROHARDNESS

Micro hardness tester (as shown in fig 4.7) was used to estimate the hardness of specimens with and without coating. The load applied was 300gm and VHN values were determined by applying this load by using a calibration distance of 50 units in quantinet. The dwell time used during load application was 25 seconds.

Figure 4.6Microhardness tester

Table 4.4 Microharness of materials

Material	Coating	Mirohardness (HV)
16Cr4Ni steel	-	350
16Cr4Ni steel	WC-Co-Cr	1390
16Cr4Ni steel	Cr_3C_2+NiCr	1090
16Cr4Ni steel	Diamlloy	880

CHAPTER 5

RESULTS AND DISCUSSIONS

The results of erosion wear are discussed in this chapter. The results are accordingly in line to the objectives defined. All erosion tests are carried for 120 minutes.

5.1 EROSION PERFORMANCE OF 16Cr5Ni STEEL

The erosion performance of 16/5 steel has been evaluated by varying velocity and impact angle. The effect of time on weight loss while varying different parameters is also evaluated with effect of each parameter. The effect of time on weight loss is reported first. The results are shown in figure 5.1 to 5.9, for all seven runs performed over a range of parameters.

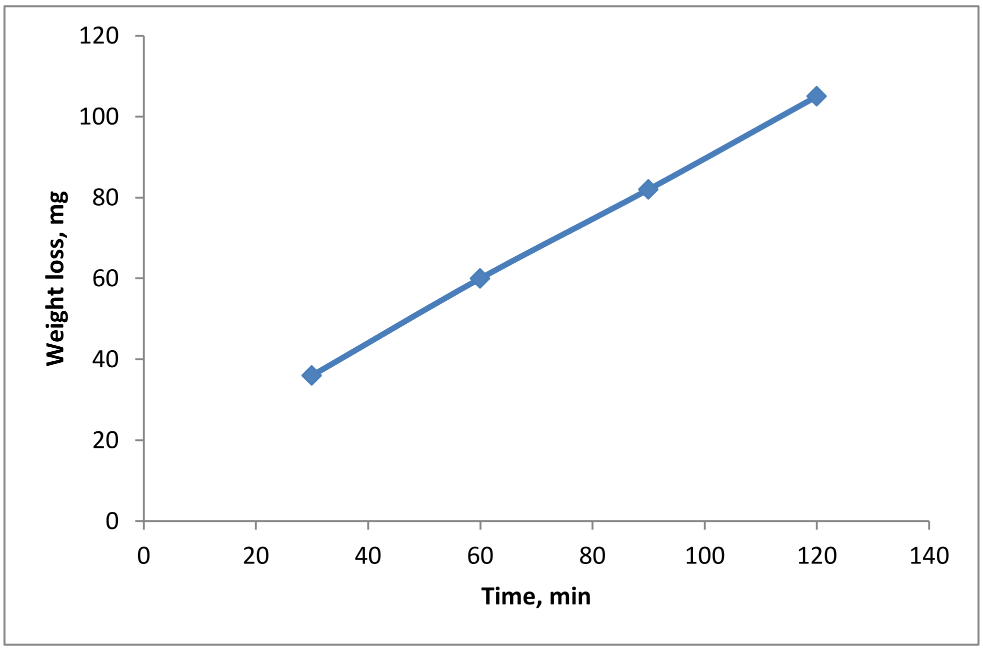

Figure 5.1 Variation of weight loss w.r.t time for run 1

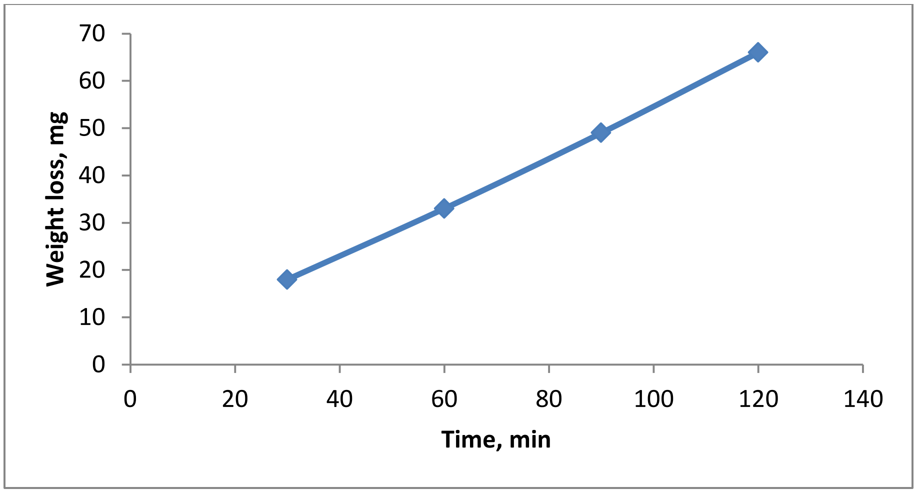

Figure 5.2 Variation of weight loss w.r.t time for run 2

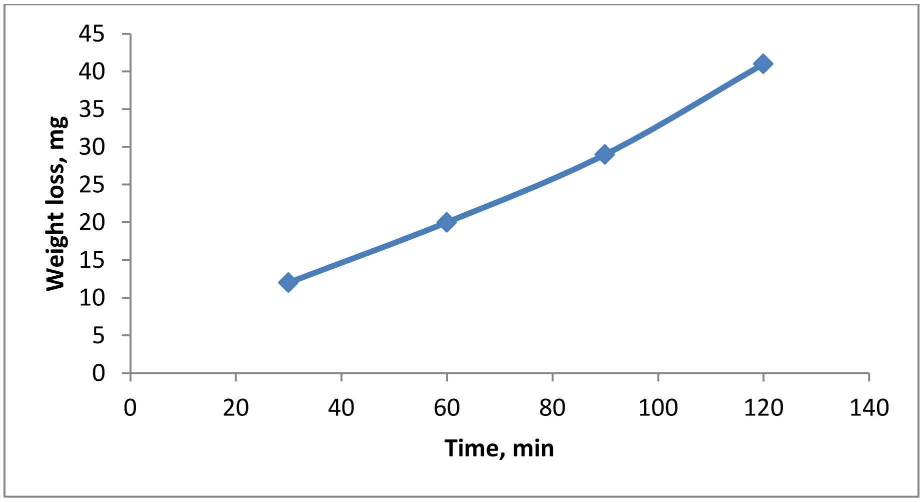

Figure 5.3 Variation of weight loss w.r.t time for run 3

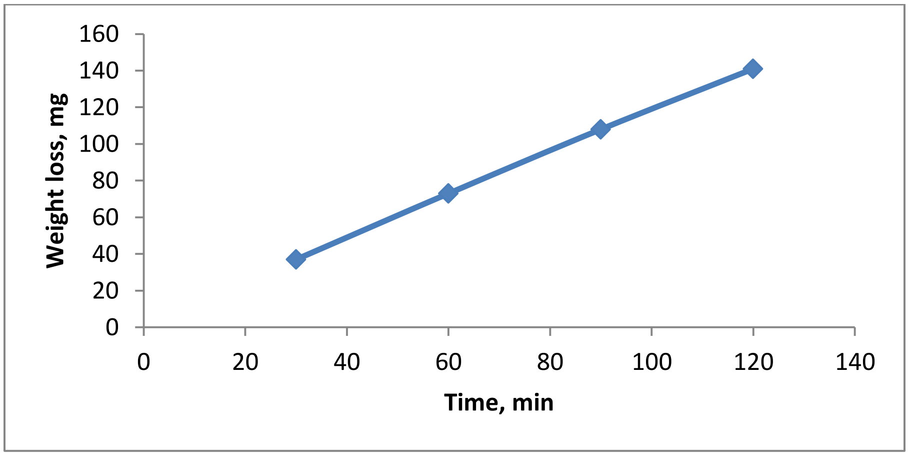

Figure 5.4 Variation of weight loss w.r.t time for run 4

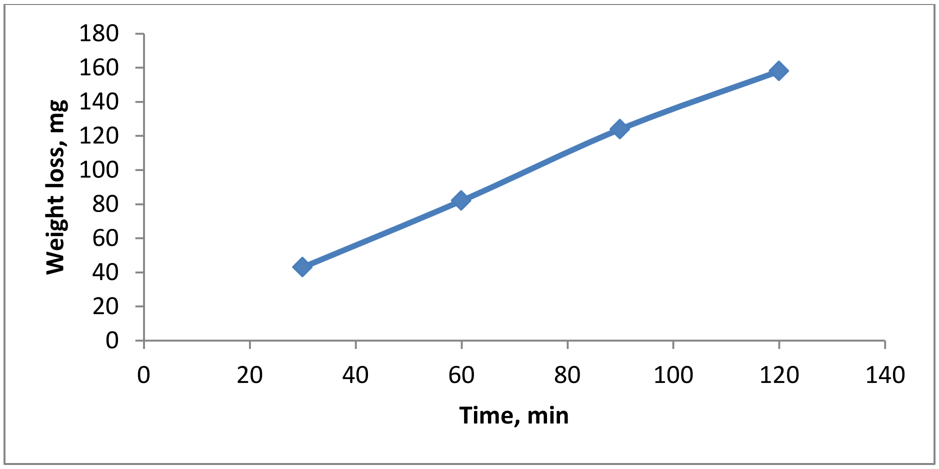

Figure 5.5 Variation of weight loss w.r.t time for run 5

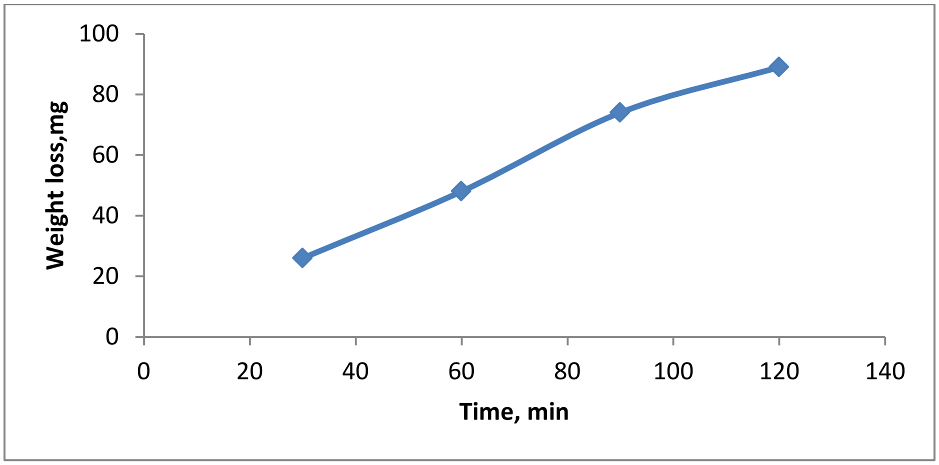

Figure 5.6 Variation of weight loss w.r.t time for run 6

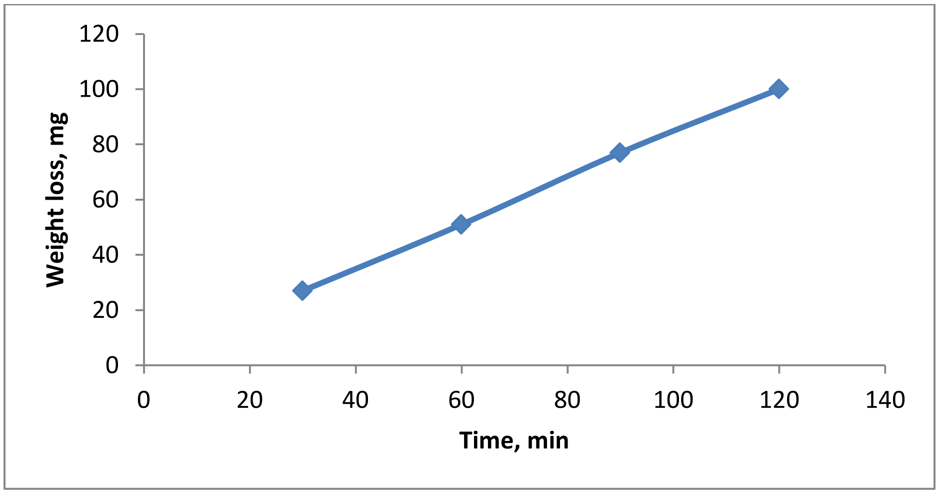

Figure 5.7 Variation of weight loss w.r.t time for run 7

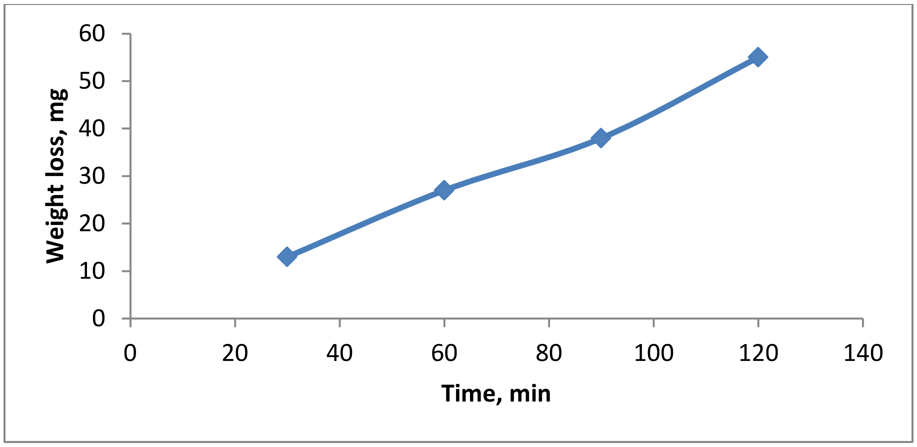

Figure 5.8 Variation of weight loss w.r.t time for run 8

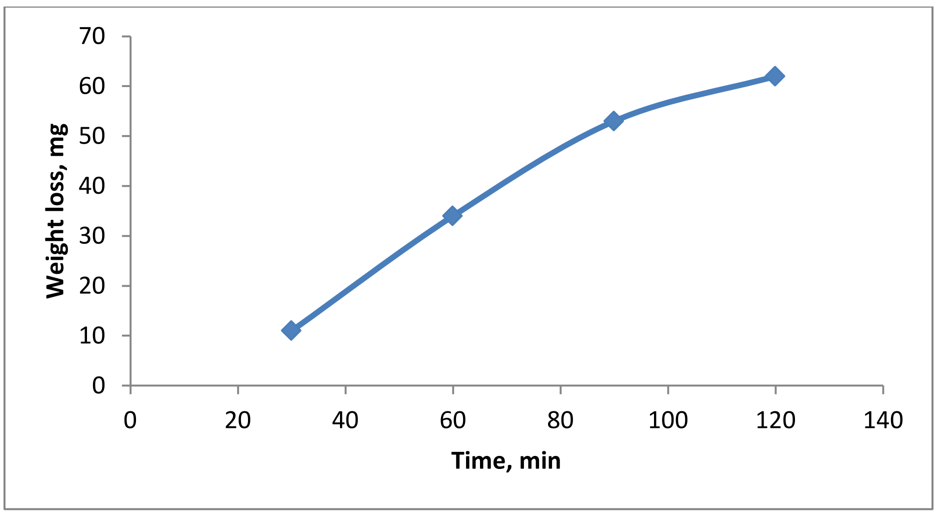

Figure 5.9 Variation of weight loss w.r.t time for run 9

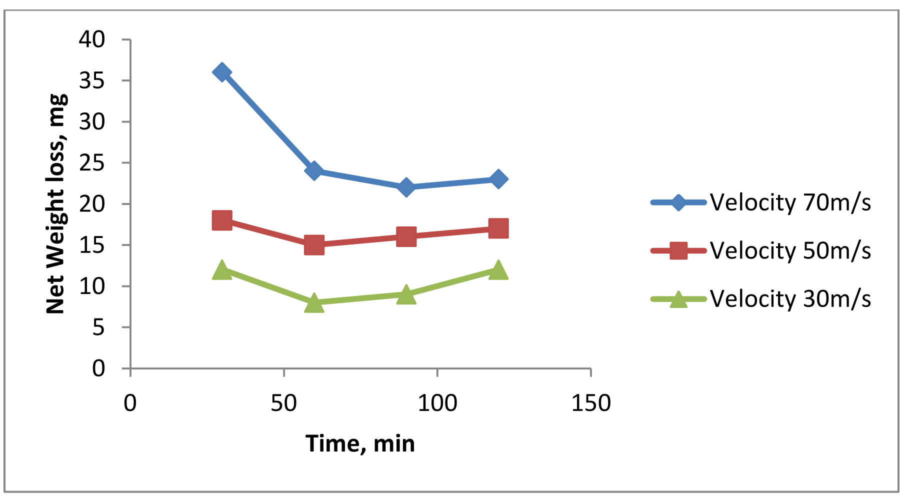

Figure 5.10 Comparison of weight loss w.r.t time for different levels of velocity

It can be clearly seen that amount of material loss increase with time which is usual. It slope of graphs is almost same throughout the run. It shows that the nearly equal amount of weight get lost in each interval of time depending upon the controlling parameters. Figure 5.10 shows the comparison of weight lost w.r.t time at different levels of velocity. Maximum weight lost is observed with velocity 70m/s, as erosion rate if function of $vel^{2.6}$ (Gandhi 1999). Figure 5.10 also shows that weight loss at initial stage is more than decrease and remains almost constant with slight increase at end.

Effect of Velocity on Erosion Wear

To evaluate the effect of velocity on erosion wear, tests were conducted at three different levels of velocity (high, medium and low velocity). The effect of velocity can be calculated by measuring the weight loss at each level of velocity. The effect of velocity on erosion wear is shown in figure 5.11.

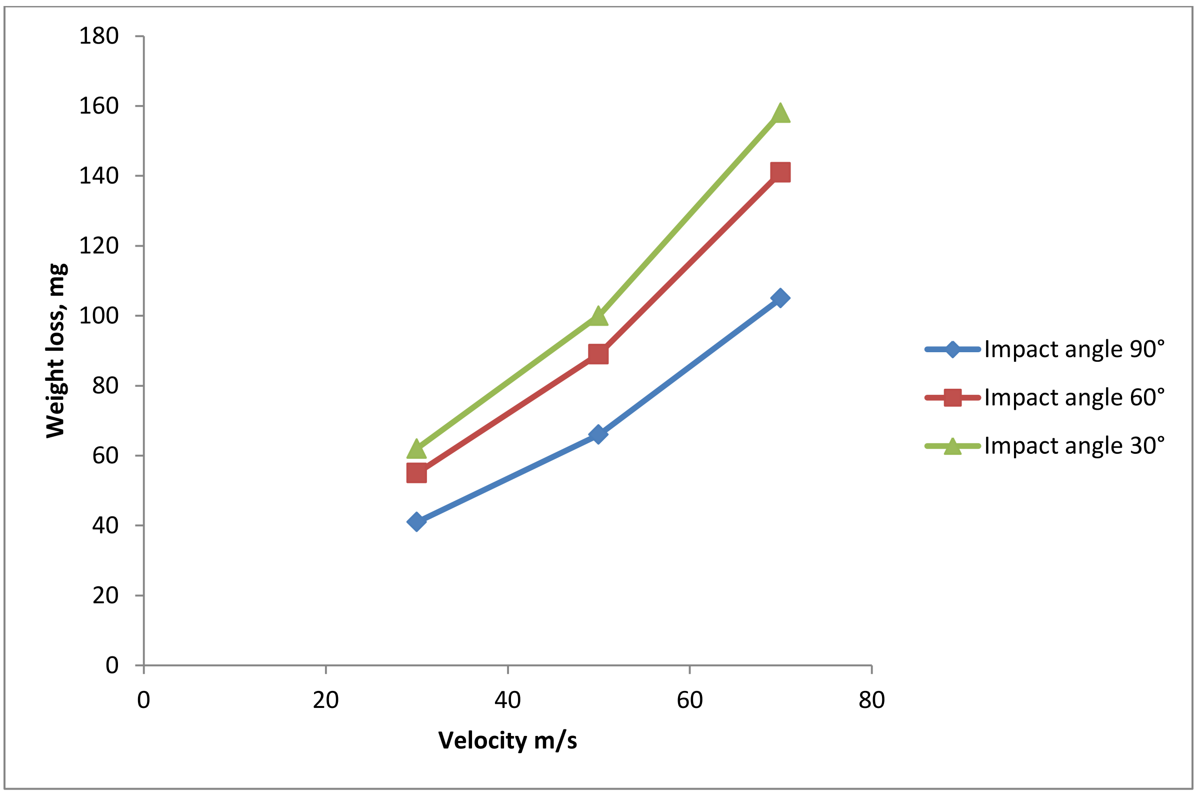

Figure 5.11 Effect of velocity on weight loss

It is clear from figure 5.11 that loss material increases with increase in velocity. The trend of effect of velocity is same at different angles. With increase in velocity, the kinetic energy of solid particle of slurry increases and thus more energy is available with erodent to deform and remove the material. A rise in weight loss is approximately 60% when velocity is increased from 30m/s to 70m/s.

Effect of Impact Angle on Erosion Wear

Impact angle has a significant effect on erosion wear and mechanism of erosion. Figure 5.12 shows the effect of impact angle on erosion.

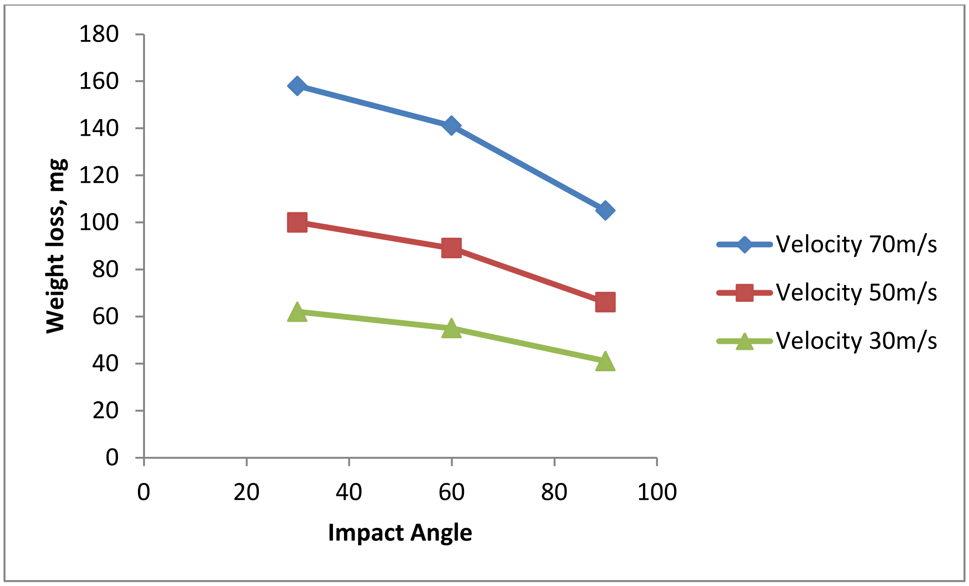

Figure 5.12 Effect of angle on weight loss

Maximum erosion occurs at 30^0 and minimum at 90^0. Higher erosion at 30^0 indicates the 16/5 steel is ductile in nature. The presence of austenitic phase is responsible of higher erosion at $30^{0.}$ Higher erosion at 30^0 could be due to microcutting mechanism. At lower angle the tangential component of velocity is responsible for the erosion. At higher angle the normal component of velocity is responsible for erosion which might cause more plastic deformation of surface and work hardening leading to reduction in weight loss.

SEM Analysis

A scanning electron microscope (SEM) is a type of electron microscope that images a sample by scanning it with a high-energy beam of electrons. The electrons interact with the atoms that make up the sample producing signals that contain information about the sample's surface topography, composition, and other properties such as electrical conductivity. The samples of material used for erosion purpose was examined with help of scanning electron microscope with aim to visualize change in microstructure in order to know the mechanism of erosion. All the samples analyzed were subjected to maximum velocity and impact angle of 90°.

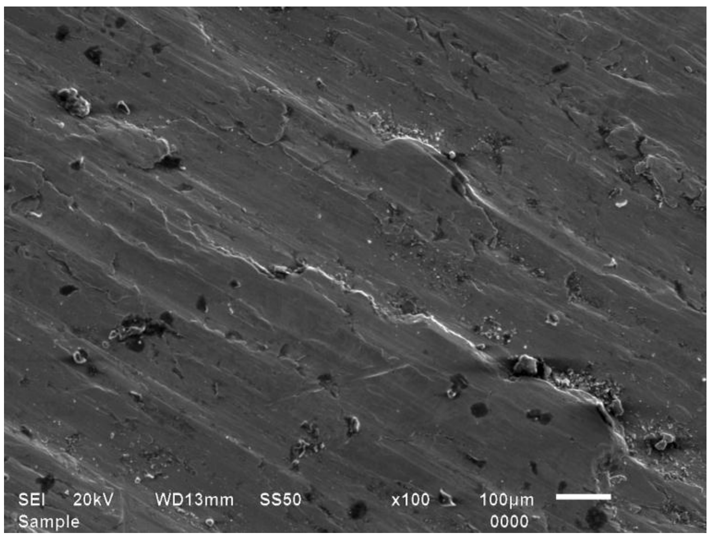

Figure 5.13(a) SEM of 16/5 steel before wear

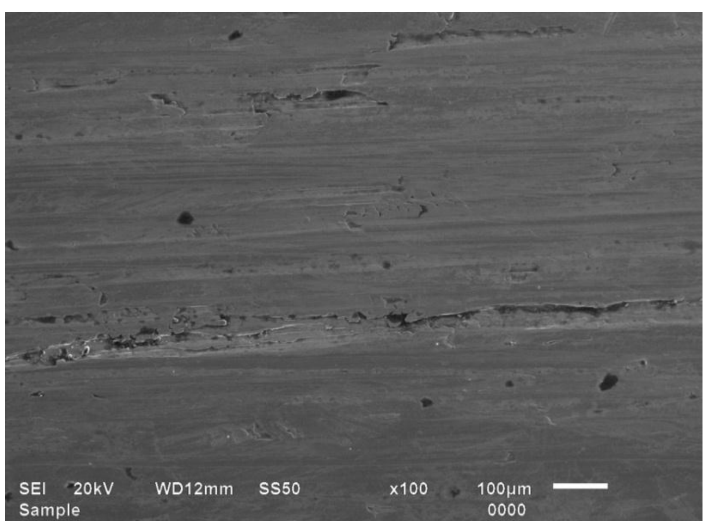

Figure 5.13(b) SEM of 16/5 steel after wear

5.2 EROSION PERFORMANCE OF COATINGS

Coatings are used to alter the surface properties of any material for any objective. The focus of present investigation was to reduce the erosion of hydro turbine components by applying different coatings using one of the promising coating methods that is HVOF thermal spray. In this section the erosion performance of coating s subject to different levels of different parameters is presented. In this section the results of studies on WC-Co-Cr, $Cr_3C_2 + NiCr$ and diamlloy is discussed one by one.

5.2.1 EROSION OF $Cr_3C_2 + NiCr$ COATINGS

This coating is known for good corrosive and erosive resistance properties. The effect of time on weight loss is presented first.

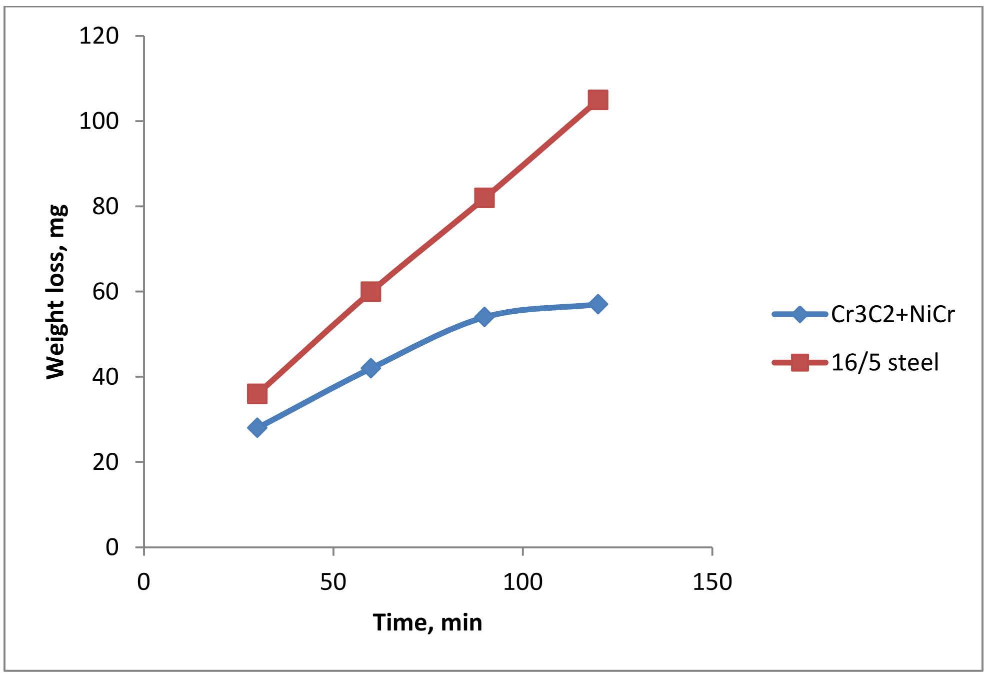

Figure 5.14 Weight loss w.r.t time for run 1

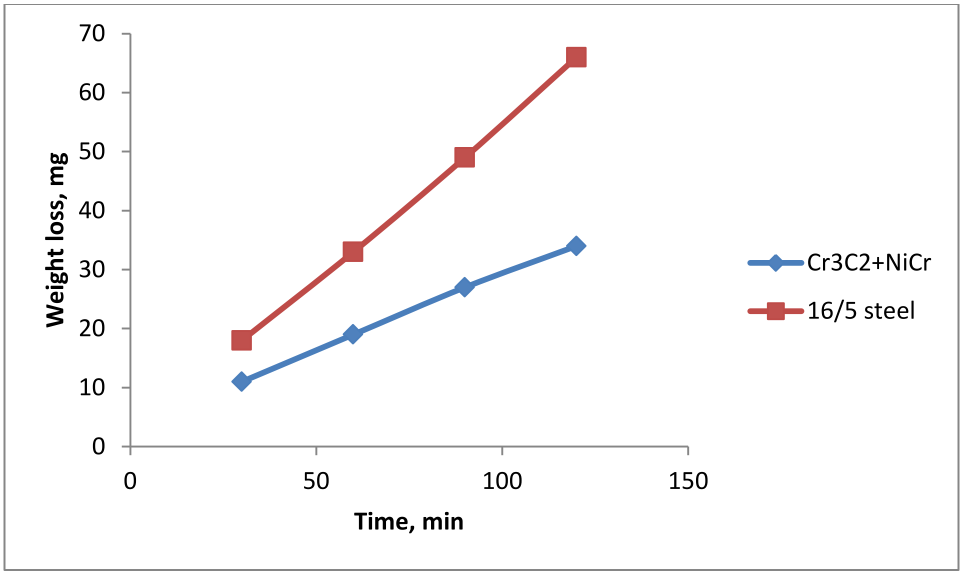

Figure 5.15 Weight loss w.r.t time for run 2

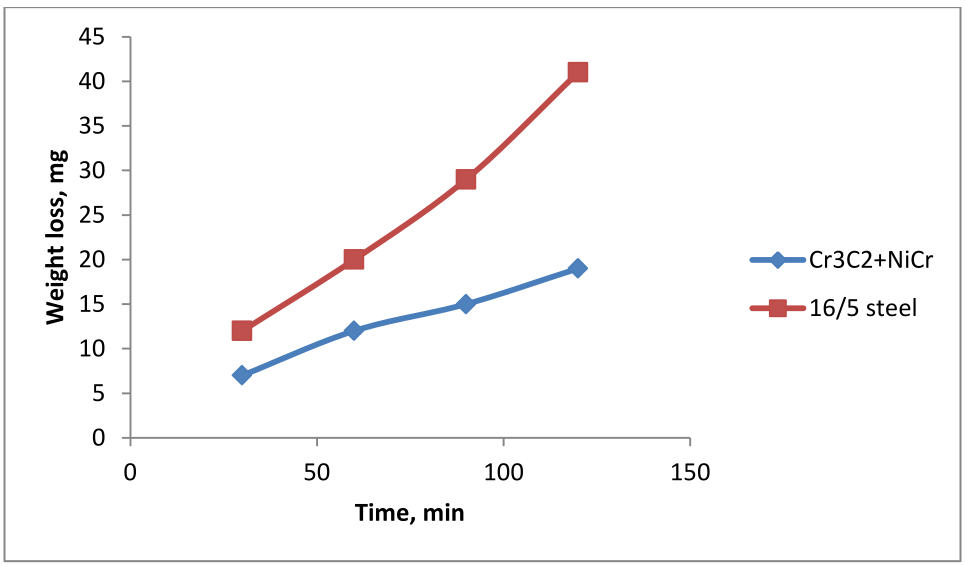

Figure 5.16 Weight loss w.r.t time for run 3

The slope of time weight graph for coated samples indicates that the weight loss for coated sample is initially higher. At the end weight loss is very less as compared to starting 30 mins. The difference in loss of weight in fist 30 min of test of coated and uncoated is not as significant as in later stages. No reason of such kind of behaviour is known, as quality of coating depends on number of parameters like velocity and temp of molten power, pressure, grain size, standoff distance, powder feed rate etc. The better bonding of coating to the substrate may be the reason for such behaviour.

Effect of Velocity on Erosion Wear

Figure 5.17 shows the effect of increase in velocity on weight loss. The comparison of effect of velocity on coated and uncoated steel is also shown

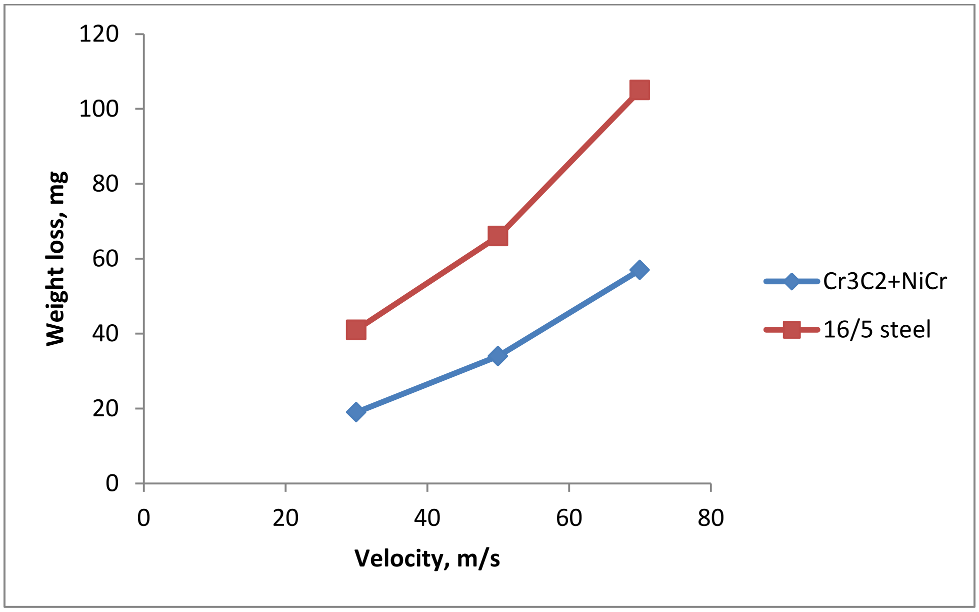

Figure 5.17 Effect of velocity on weight loss for $Cr_3C_2 + NiCr$ coatings

With increase in velocity erosion also increases. The trend of curve is almost similar to that of 16/5 steel. The erosion of coatings takes place by fatigue mechanism leading to micro cracks. The high kinetic energy of solid particles of slurry causes the cracks and with repetitive action the fracture of coatings takes place with advancing of these cracks.$Cr_3C_2 + NiCr$ coating clearly shows better erosion resistance than 16/5 steel at all different levels of velocity.

Effect of Impact Angle on Erosion Wear

Impact angle is very important parameter in erosion study. At lower angle microcutting mechanism is predominant and at higher angles crack intimation is more predominant. The effect of angle on $Cr_3C_2 + NiCr$ and comparison with uncoated 16/5 steel is shown in figure 5.18 which will help to decide the mechanism of erosion.

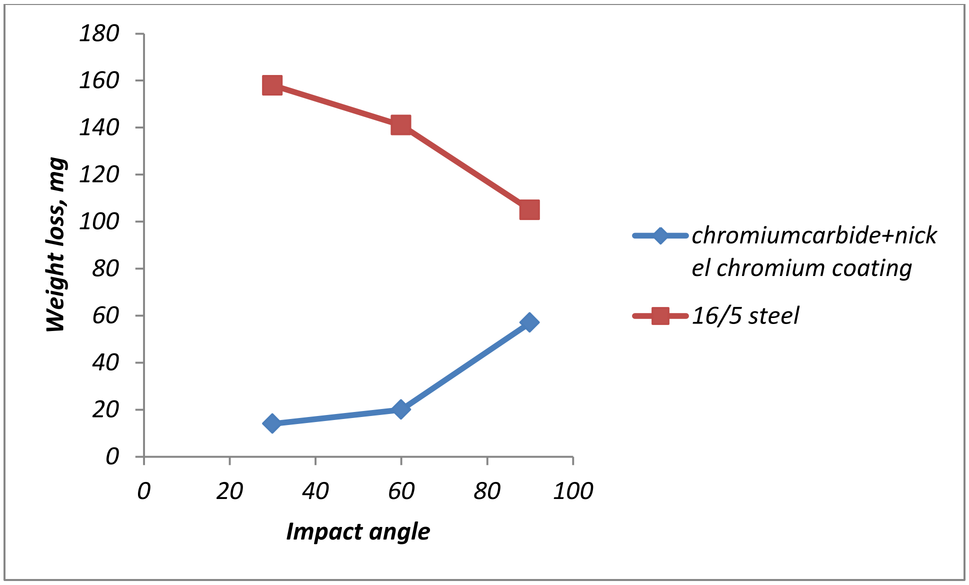

Figure 5.18 Effect of impact angle on Wt loss for$Cr_3C_2 + NiCr$

The slope of $Cr_3C_2 + NiCr$ curve indicates that maximum erosion is at 90^0 and minimum at 30^0. Whereas for 16/5 steel maximum erosion is observed at 30^0 and minimum at 90^0. This indicates that $Cr_3C_2 + NiCr$ is brittle in nature, but 16/5 steel has ductile nature. The erosion mechanism at lower angles is because tangential component of velocity and at higher angles normal component of velocity causes the erosion. With tangential component of velocity micccrocutting and ploughing mechanism is predominant and with normal component of velocity cracking is predominant. By increasing the angle weight loss also increases. The $Cr_3C_2 + NiCr$ coatings show better performance than 16/5 steel. The difference in weight loss at lower angle is very high as compared to higher angles. At lower angle erosion of $Cr_3C_2 + NiCr$ is almost 10% of 16/5 steel whereas at 90^0 the weight loss of $Cr_3C_2 + NiCr$ is half of that of 16/5 steel. At lower angles the effect of bond strength of coating is more than at normal angle.

SEM Analysis

SEM analysis [Figure 5.19 (a), (b)] shows that the mechanism of erosion of 16/5 steel is platelet mechanism. Microstructure of coating shows that it pores and contains voids at its surface.

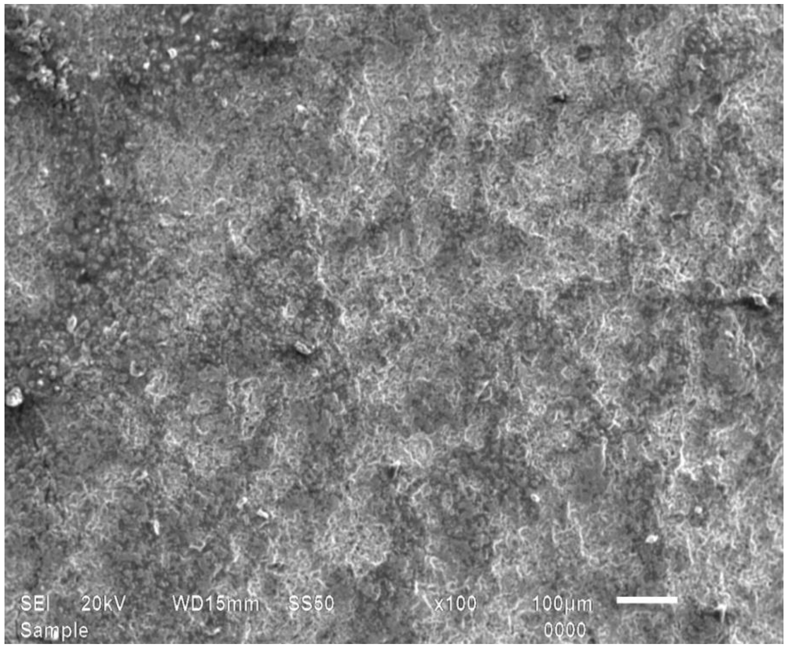

Figure 5.19 (a) SEM of $Cr_3C_2 + NiCr$ before wear

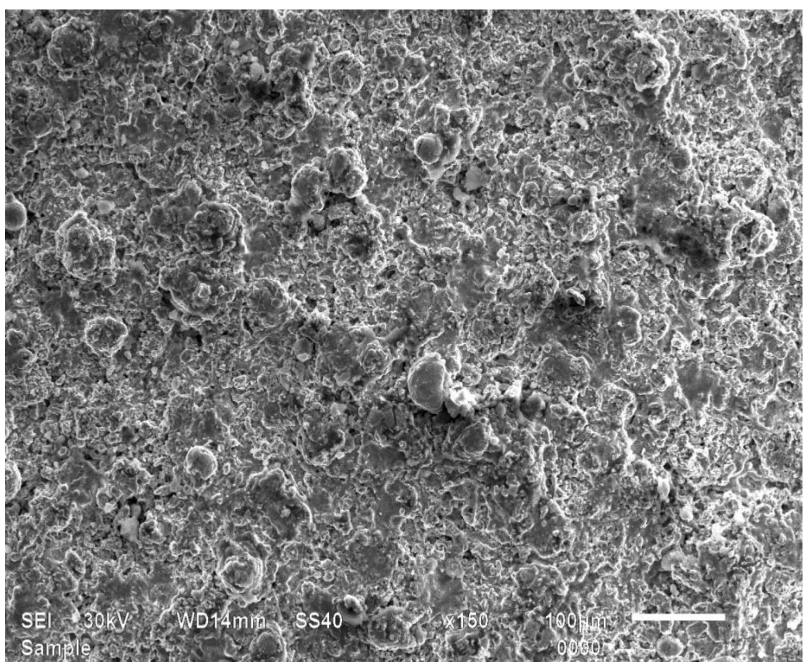

Figure 5.19 (b) SEM of $Cr_3C_2 + NiCr$ after wear

5.2.2 EROSION OF WC-Co-Cr COATINGS

The result of study of erosion on WC-Co-Cr is presented in this section. WC-Co-Cr is very hard in nature. The weight loss with respect to time is presented below.

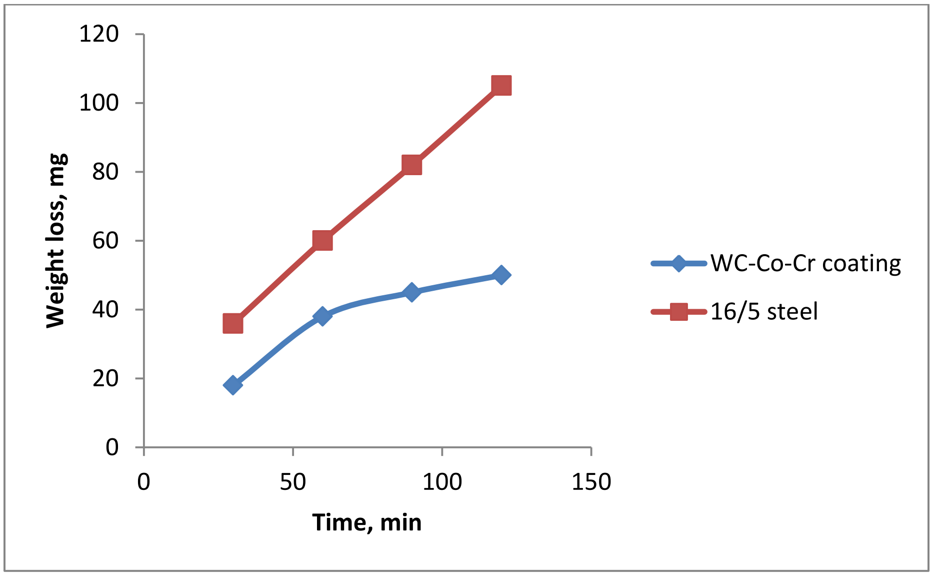

Figure 5.20 Effect of weight loss w.r.t time for run 1

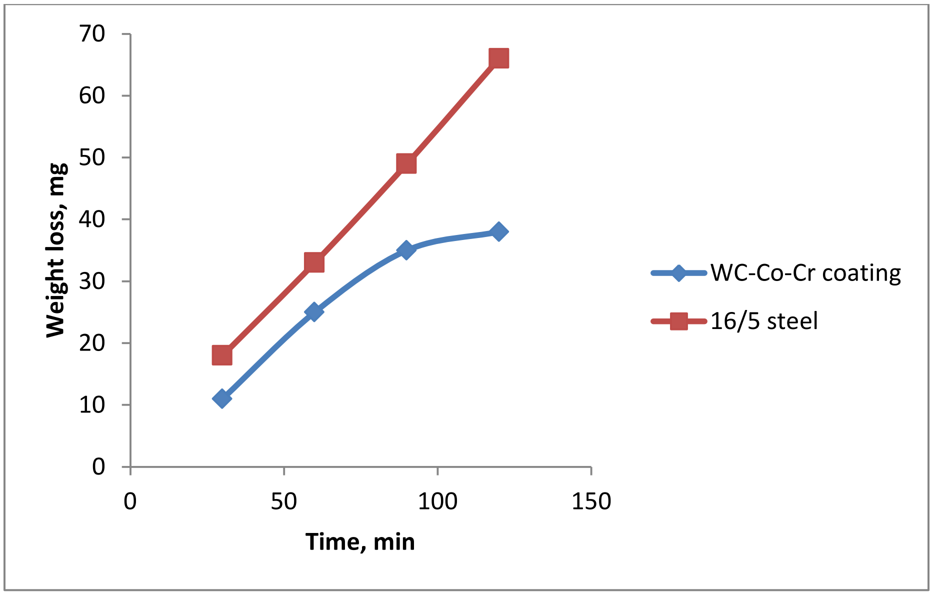

Figure 5.21 Effect of weight loss w.r.t time for run 2

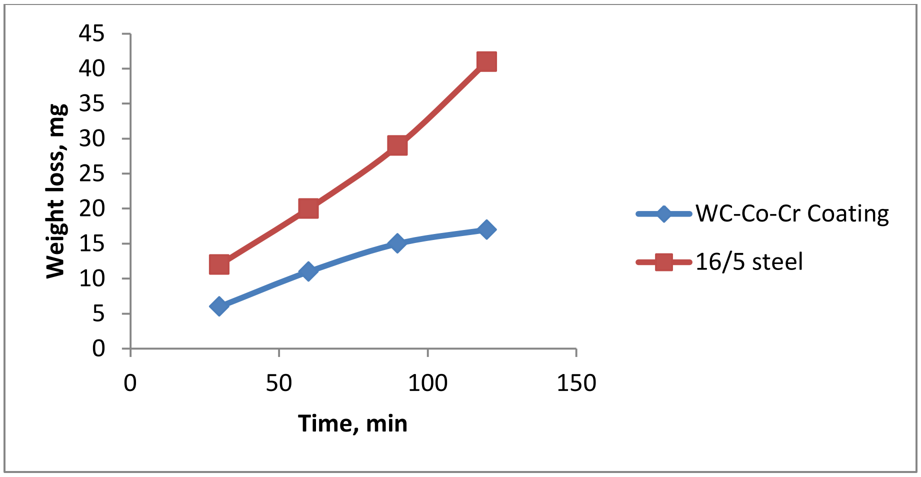

Figure 5.22 Effect of weight loss w.r.t time for run 3

The erosion of WC-Co-Cr coating is very much lower than 16/5 steel. Figure 5.20 to 5.22 shows that all the curves follow the same trend. The weight loss in initial period of time is higher thereafter decreasing in stage in all runs. Whereas the weight loss of 16/5 steel is almost uniform for all spans of time. The reason for such behaviour of WC-Co-Cr is not exactly defined, as strength of coating depends on number of operating parameters.

Effect of Velocity on Erosion Wear

The effect of velocity on erosion of WC-Co-Cr is presented in this section. Figure 5.23 shows the effect of velocity on erosion of coating and comparing it with 16/5 steel.

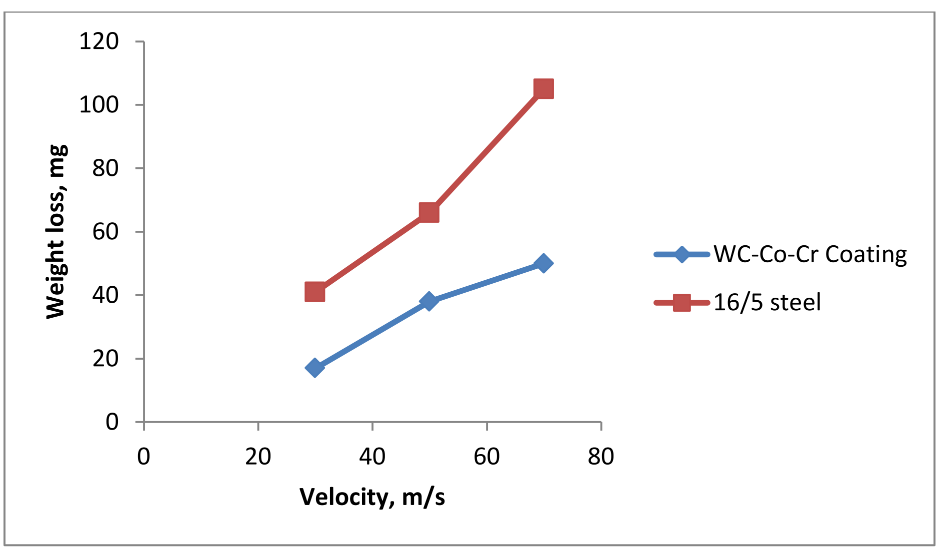

Figure 5.23 Effect of velocity on weight lossof WC-Co-Cr coating

Weight loss of coated sample increases with increase in velocity. The weight loss is because of tangential or normal component of velocity is decided by the impact angle. At higher velocity, the solid particles of erodent, which causes erosion, posses higher kinetic energy. Higher energy develops the cracks in coating by fatigue mechanism. As the velocity is increased the tendency of rooting the loosely bonded increases, thus increasing the velocity increases the weight loss. Slope shows that weight loss is more when velocity is increased from 30 to 50 m/s than 50 to 70 m/s. About 60% weight loss is observed when velocity is increased from lower level to medium level of velocity. The weight loss of coating is very less as compared to 16/5 steel sample. Weight loss of coating is about half of the weight loss in bare 16/5 steel sample.

Effect of Impact Angle on Erosion Wear

Impact angle is important parameter to decide the erosion rate and mechanism of erosion. For ductile materials maximum erosion is observed at impact angle of 30^0, and at 90^0 for brittle material. Thus effect of angle also indicates the nature of material. Figure no 5.22 shows the effect of impact on erosion of WC-Co-Cr coating at comparing it with effect on16/5 steel.

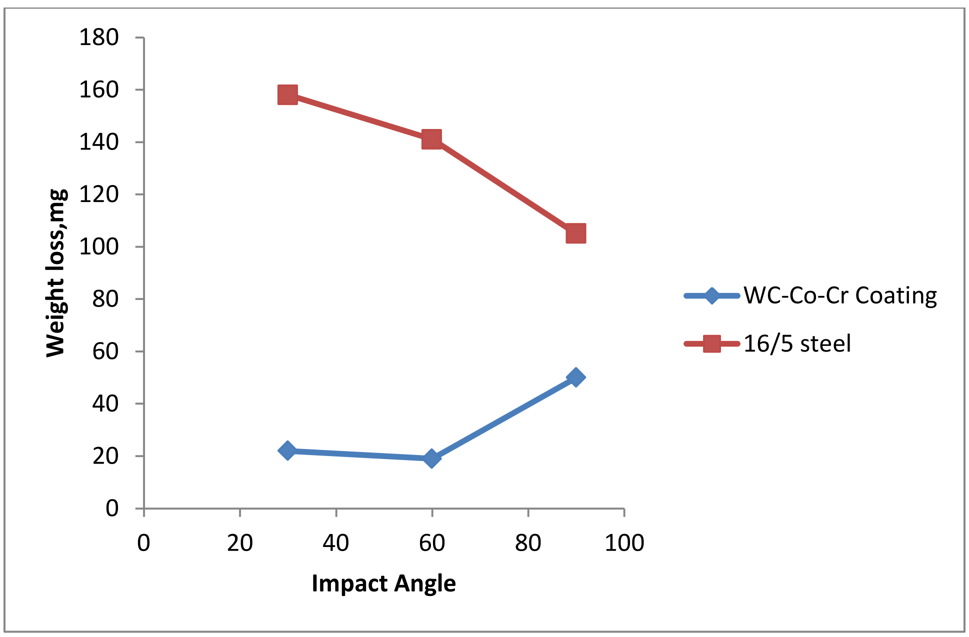

Figure 5.24 Effect of impact angle on weight loss of WC-Co-Cr coating

The erosion of WC-Co-Cr coating increase with increase in impact angle. Max erosion is observed at 90^0, thus brittle mode of failure. Weight loss is less at lower angle for the coating. A slight decrease in weight loss is observed when angle is changed from 30^0 to 60^0. Weight loss at 90^0 is nearly half of the 16/5 steel. At smaller angles coating shows 8 times better performance than 16/5 steel. Erosion at 90^0 is because of normal component of velocity, causing fatigue and fracture of grain boundaries. As max erosion is observed at 90^0, thus WC-CO-Cr coating is brittle in nature. Whereas 16/5 steel is ductile.

SEM Analysis

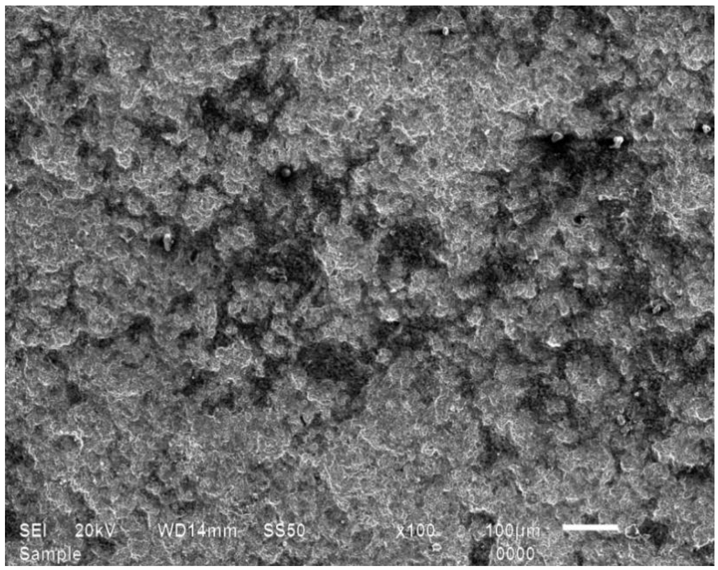

Figure 5.25 (a) SEM of WC-Co-Cr before wear

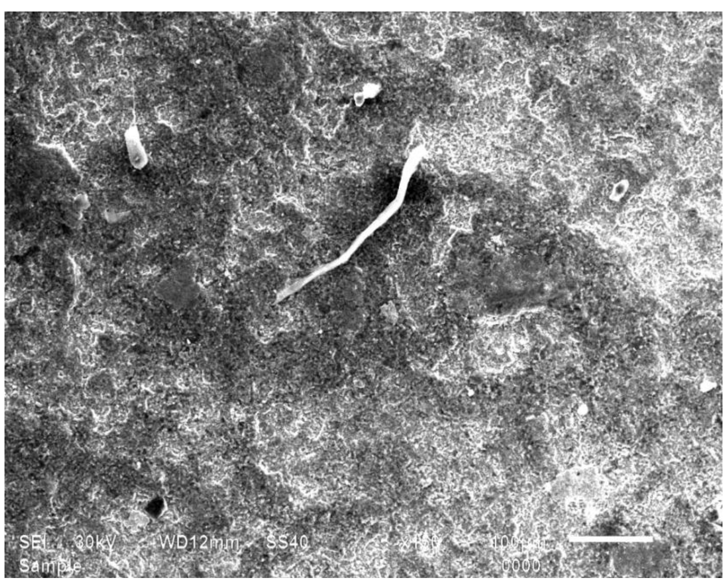

Figure 5.25 (b) SEM of WC-Co-Cr after wear

5.2.3 EROSION OF DIAMLLOY COATINGS

Erosion performance of diamlloy coating is discussed in this section. Weight loss w.r.t time is presented first. Figure 5.26 to 5.28 shows the weight loss over the time span of 2hrs.

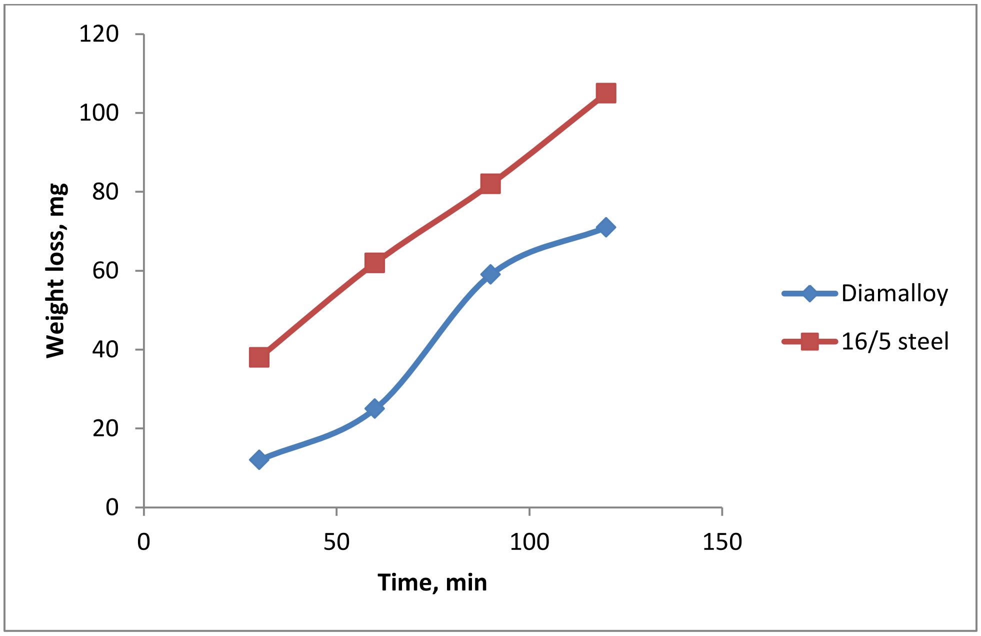

Figure 5.26 Weight loss w.r.t time for run 1

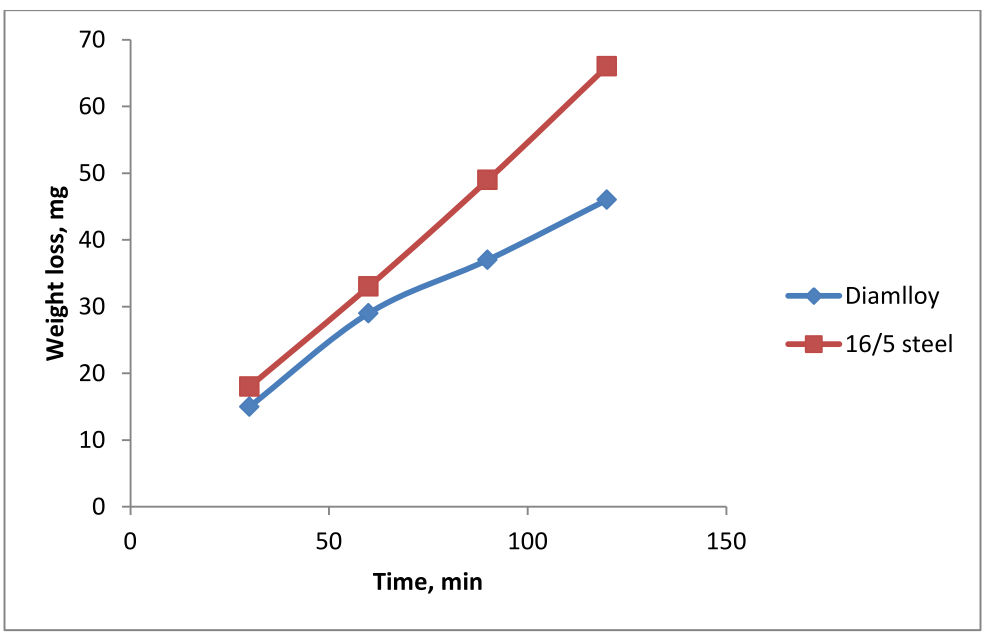

Figure 5.27Weight loss w.r.t time for run 2

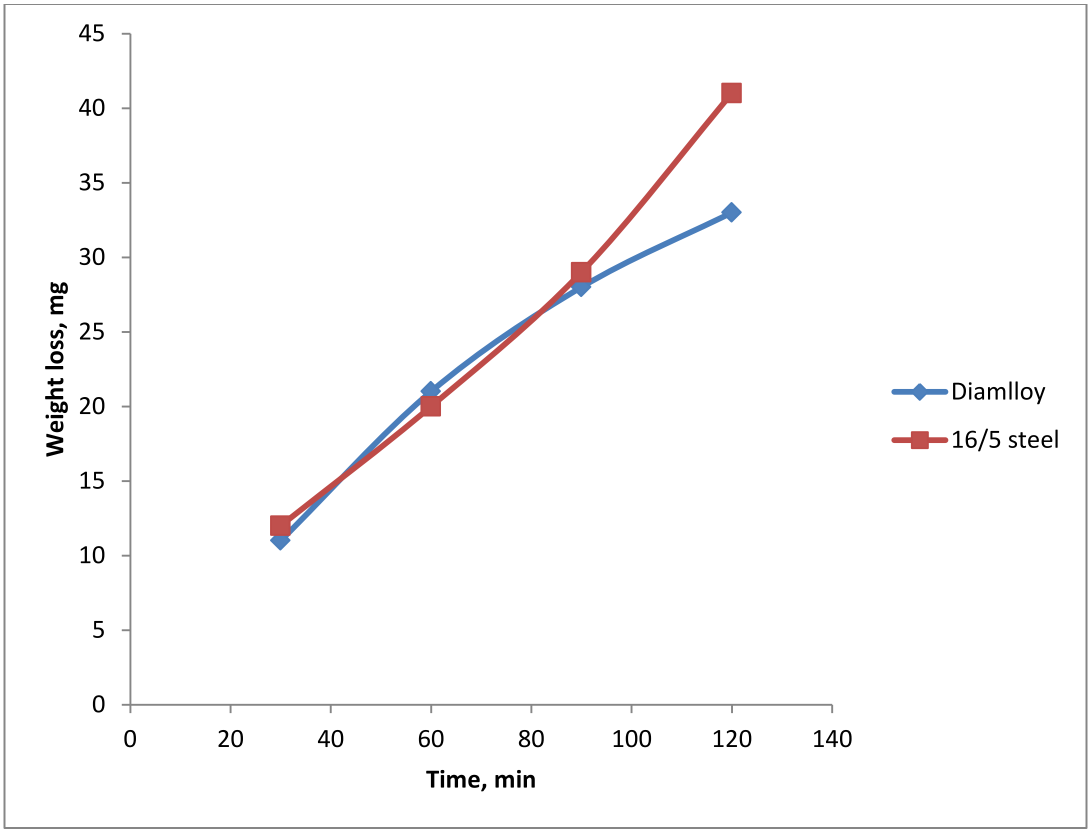

Figure 5.28 Weight loss w.r.t time for run 3

Initially the weight loss is more as compared to later stages. In figure 5.26 increase in weight loss at later stage w.r.t is observed. Max weight loss is observed in time run of 60 to 90 min. Whereas in other runs max erosion is within time period of 1st hr. Figure 5.28 shows that almost same amount of weight has loss for 1.5 hr and in last 30 min erosion of diamlloy coating is less than 16/5 steel. In 1sthr diamolly coating erodes more than 16/5 steel.

Effect of Velocity on Erosion Wear

The effect of velocity on weight loss is shown in figure 5.29. Figure shows that weight loss is directly proportional to velocity of jet striking the specimen.

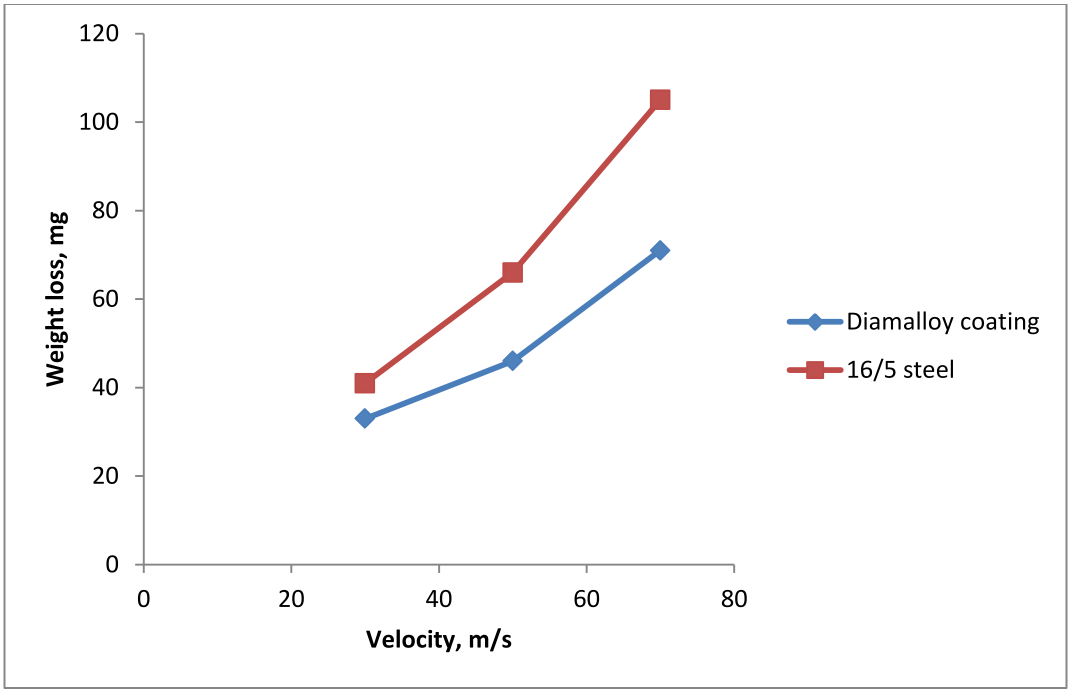

Figure 5.29 Effect of velocity on weight loss of diamlloy coating

More the velocity is more the energy solid particle of slurry posses. The high kinetic energy of the solid particles causes the cracks to intimate at the boundaries and with repeat action fracture of coatings takes place with advancing of these cracks. More the kinetic energy is more the weight will be loss. The trend of weight loss of diamlloy coating is almost similar as of 16/5 steel, but weight loss of diamlloy coating is less as compared to 16/5 steel. The weight loss of diamlloy coating is 30% less than 16/5 steel.

Effect of Impact Angle on Erosion Wear

Impact angle of erodent play significant role in erosion and its mechanism. At lower angles cause of erosion is microcutting and at higher angles crack formation due to fatigue mechanism causes the erosion. The effect of angle on erosion of diamlloy is shown in figure 5.30.

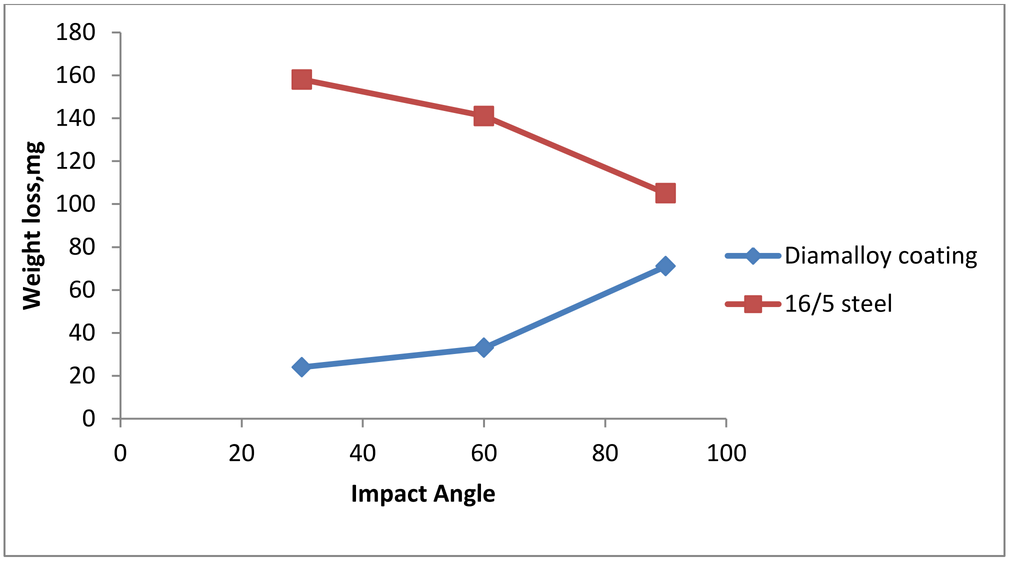

Figure 5.30 Effect of impact angle on weight loss of diamlloy coating

Maximum weight loss of diamlloy coating is at 90^0 and minimum is observed at 30^0. When angle is increased from 30^0 to 60^0 a small increment in weight loss is observed, but further increasing to 90 significant increment is noted. Weight loss by increasing angle from 60^0 to 90^0 is approximately 3.5 times more than changing angle from 30^0 to 60^0. At 30^0diamlloy shows 6 times better performance than 16/5 steel. At 90^0 also diamlloy shows better performance than 16/5 steel.

SEM Analysis

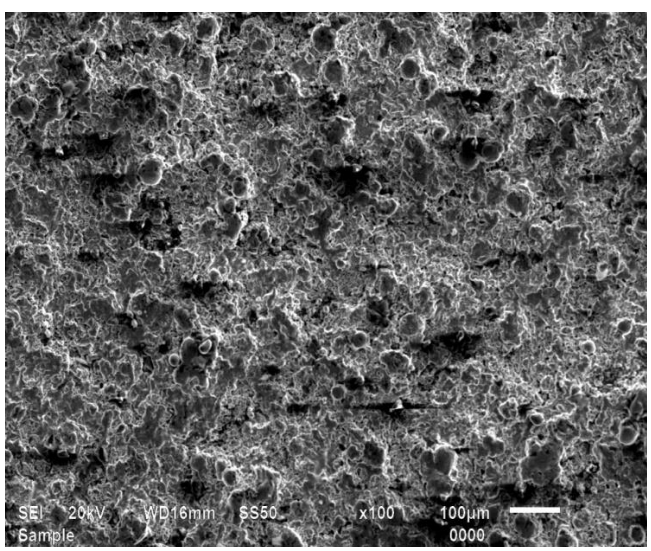

Figure 5.31(a)SEM of diamlloy before wear

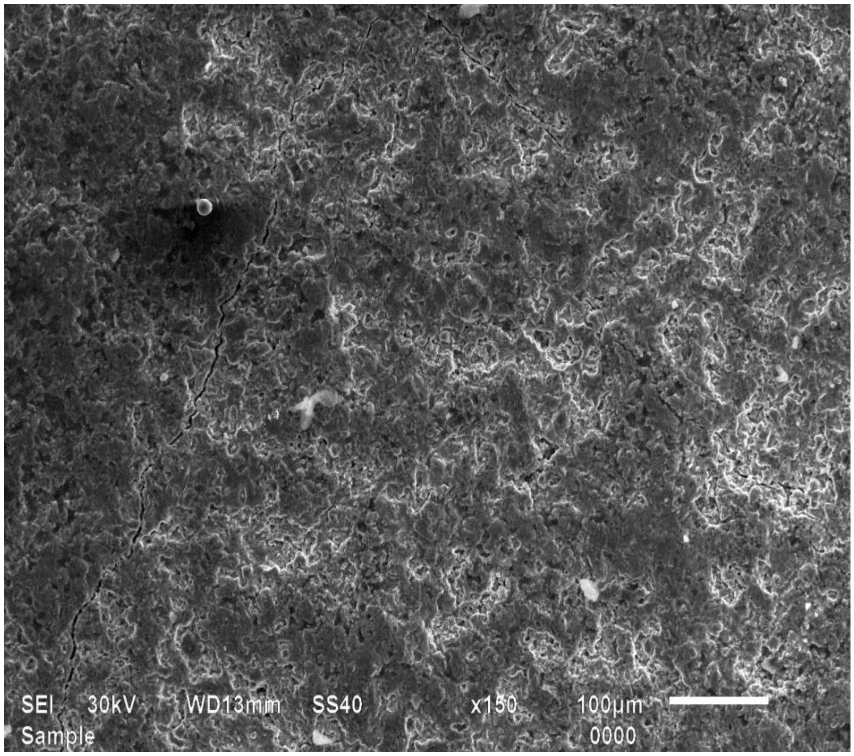

Figure 5.31(b)SEM of diamlloy after wear

Micrstructure of diamlloy shows that the erosion mechanism is crack formation due to faigue. The cracks in this coating is more wider than other coatings which result in more weight loss of diamlloy cotaings. If time of test is increasesd the coating will fail, can get remove from the suface of base material.

5.3 COMPARISON OF UNCOATED STEEL AND VARIOUS COATINGS

HVOF thermal spray coatings have been applied on 16/5 steel to alter its surface properties to enhance its wear resistance. In this section comparison between the performance of various coatings and uncoated steel is presented. These comparisons will analysis whether coatings help to improve performance against erosion or not. All different operating parameters were varied. The comparison of weight loss w.r.t to time is shown below.

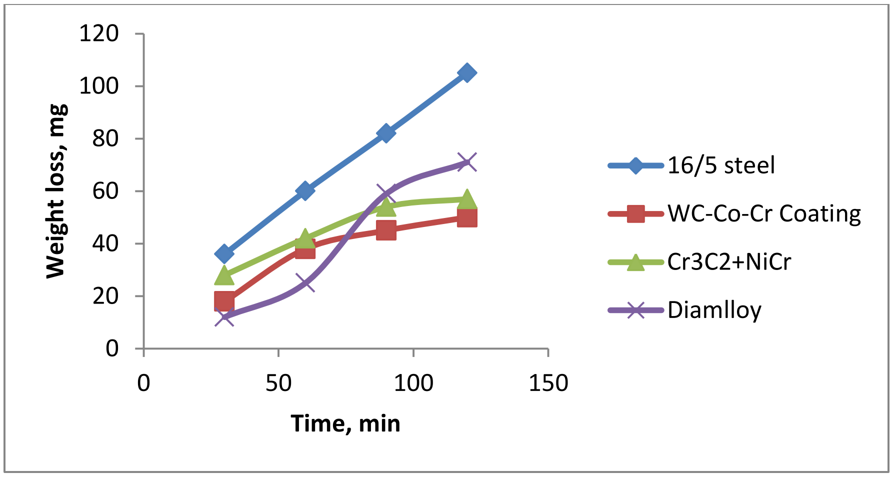

Figure 5.32 Comparison of weight loss w.r.t time for run 1

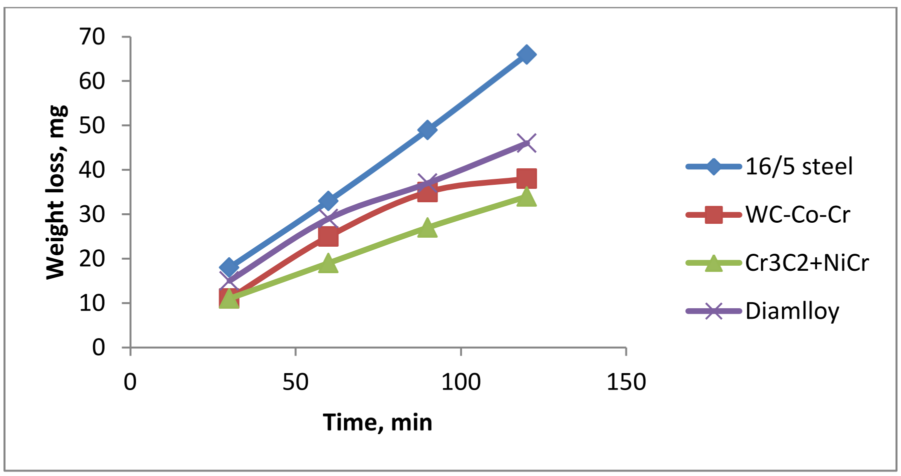

Figure 5.33 Comparison of weight loss w.r.t time for run 2

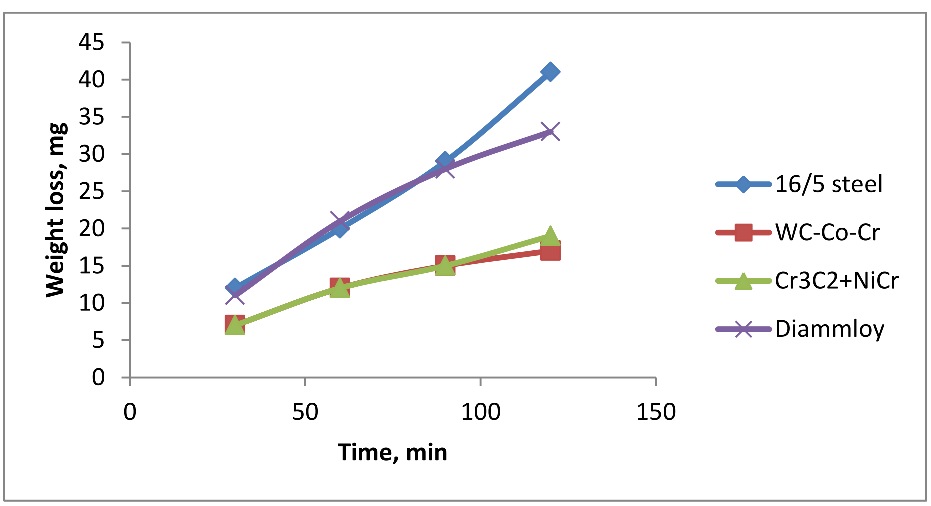

Figure 5.34 Comparison of weight loss w.r.t time for run 3

It is clear from the above figures that weight loss of coated sample is less than the uncoated 16/5 steel. For the coated samples the weight loss in 1^{st}hr is more as compared to 2^{nd}hr, whereas in uncoated samples weight loss remains constant throughout the run. In figure 5.32 curve of diamlloy coating shows that weight loss in 1^{st}hr is less than as in 2^{nd}hr but same curve in figure 5.33 and 5.34 follows the trend as in other, i.e. initial weight loss is more.

Effect of Velocity on Erosion Wear

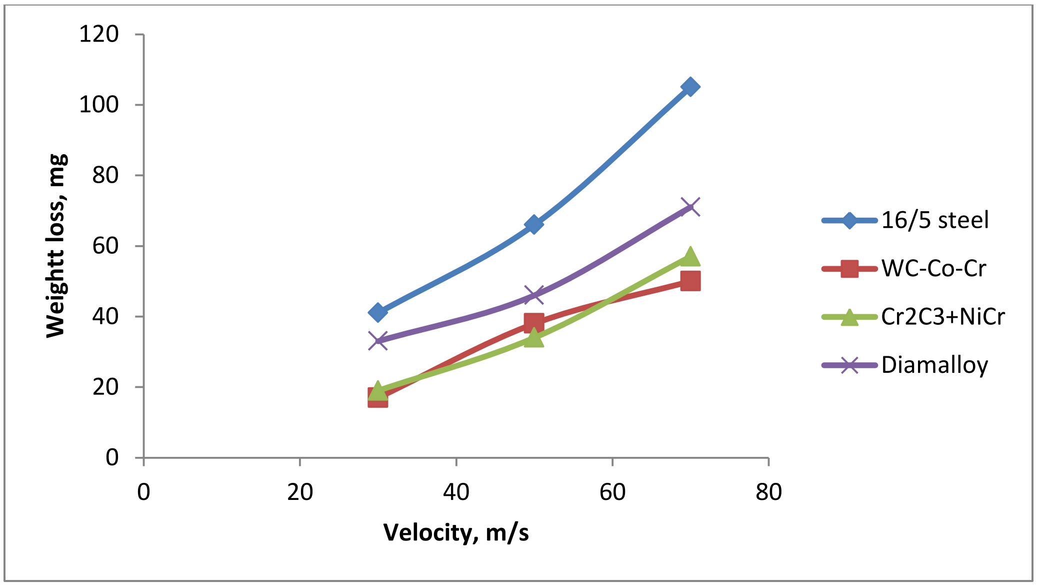

Figure 5.35 Comparison of effect of velocity

Figure 5.35 shows the effect of velocity on various coatings and uncoated 16/5 steel. The effect of velocity is almost same for all the coatings and uncoated steel. The weight loss increases as velocity is increased from lower level to medium level (30m/s to 50m/s). The increase in weight loss is more when velocity is further increased to 70m/s. But WC-Co-Cr coating shows different pattern. Increase in weight loss is less as compared to when level was increased from lower to medium level. The effect of velocity is clear from figure 5.35 that erosion wear increases with increase in velocity.

Effect of Impact Angle on Erosion Wear

Coatings alter the surface properties, so impact angle is important parameter to study erosion wear of coatings, as it can provide some idea about structure of coatings and mechanism of erosion mostly responsible for its failure. At smaller angle microcutting and ploughing mechanism is more predominant and at larger angles by fatigue and fracture mechanism. The effect of impact angle is shown in figure 5.36.

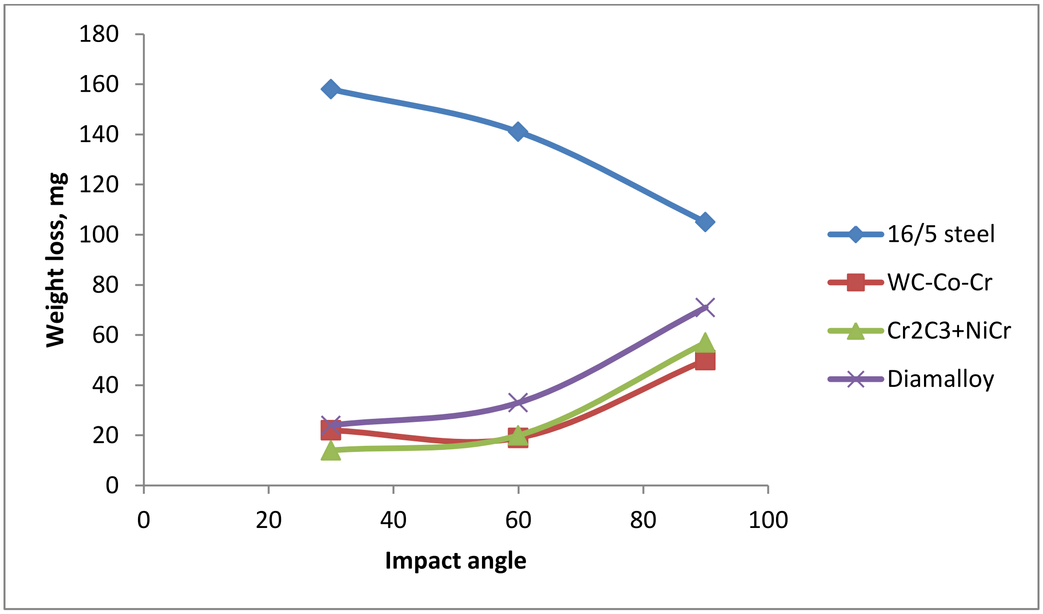

Figure 5.36 Comparison of effect of impact angle

All coatings has maximum erosion at 90° whereas for uncoated steel have minimum erosion. 16/5 steel has maximum erosion at 30°. At 30, $Cr_3C_2 + NiCr$ and diamlloy coating has minimum weight. But WC-Co-Cr has loss minimum weight at 60°. Coatings shows better performance than uncoated steel at all angles.

As per the results and discussions in previous section it has been noticed that coatings help to improve the resistance against erosion. Coatings have shown better performance at each level of different operating parameters (velocity and impact angle).

From figure 5.32 to 5.36 it is clear that WC-Co-Cr has given the best performance against erosion. Diamlloy coating has given poorer performance among three different coatings. $Cr_3C_2 + NiCr$ has also shown good performance. WC-Co-Cr coating posses very good erosion resistance followed by $Cr_3C_2 + NiCr$ and diamlloy.

CHAPTER 6

CONCLUSIONS

The mostlycommonly used turbine material 16/5 steelisselected as a base material. The HVOF thermal spray coatings method is used for coating of different powders, WC-Co-Cr, Cr_3C_2+NiCr and diamlloy. The erosion rate evaluated with varying the parameters impact angle and velocity of flow of sand slurry. The erosion wear rates are evaluated in terms of weight loss of material using jet erosion tester. The conclusions of the experimentation result are listed below:

- Erosion wear rate of 16/5 steel is found uniform with respect to time.
- Coatings show better performance than uncoated steel in all conditions in which test was performed.
- WC-Co-Cr coating shows the minimum wear rate among the other coatings, Cr_3C_2+NiCr and diamlloy. The maximum erosion wear rate found with diamlloy coatings.
- Erosion wear rate with coating is observed that higher in initial running hours and reduces with respect to time.
- WC-Co-Cr coated steel shows approximately 3 times better performance than 16/5 uncoated steel.
- For 16/5 uncoated steel maximum erosion is at 30° impact angle and minimum at 90°.
- For all coatings maximum erosion is at 90°.
- Only WC-Co-Cr coating has minimum erosion at 60° .
- At higher angles WC-Co-Cr coated steel shows better performance but at lower angles Cr_3C_2+NiCr shows a slightly better performance.
- The erosion mechanism of 16/5 steel under normal impact is platelet mechanism but for coating under similar condition is due to crack formation.

FUTURE SCOPRE

- The erosion wear studies can be performed with other coating techniques.
- The computational approach can be used to simulate the similar work with different operating conditions.
- The effect of erosion wear of pump impeller of ash disposal system can be studied.
- The similar erosion wear studies can be extended by using other types of pot tester and different slurry concentration.

CHAPTER 7

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ANNEXURE

RUN	VELOCITY M/S	ANGLE	CONCENTRATION %
1	70	90	3
2	50	90	3
3	30	90	3
4	70	60	3
5	70	30	3
6	50	60	3
7	50	30	3
8	30	60	3
9	30	30	3