Erosive behaviour of HVOF Sprayed Coatings: A Review

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Abstract

Slurry erosion of turbine components in hydro power plants is a serious problem faced all over the world. Researchers are continuously working on investigating the ways to mitigate the effect of slurry erosion. Different techniques are employed to protect the material from deteoriation of its life, techniques such as filtration of the sand particles were carried out to reduce the amount of sand particles in the water which is impacting on the turbine components and designing the shape of turbine components in such a manner so as to mitigate the effect of slurry erosion. Still slurry erosion is most priortize area among the researchers as it is causing heavy economic losses. As a new alternative, researchers are exploring the thermal spray coating technique as an option by which the surface properties of the material will be improved. Thermal spraying is one of the most prominent methods used now a days to prevent the material from abrasive wear, high temperature corrosion, erosive wear and stresses, as it increases the life span of material used in service. High velocity Oxy Fuel (HVOF) spraying is among the thermal spraying techniques which are known for its various characteristics such as providing hardness, wear resistant and dense micro structured coatings. In this paper an attempt has been made to present a state of art review of the work done by various researchers to prevent slurry erosion of hydraulic machine components by using HVOF Spray technique.

Keywords: Thermal spraying, HVOF, erosion.

Introduction

In the present era of developing world, there is a growing need for industrialization. To fulfill this need industry requires energy sources to cater its demand. In particular demand of electrical energy is increasing rapidly day by day [1]. Hydropower being a renewable source of energy has fascinated the attention of researchers worldwide for harnessing its potential to fulfill the increasing demand of energy requirement [2-4]. With increasing dependency on hydropower, more burdens have been put on hydroelectric power plant which has resulted in extensive utilization of available hydro power resources. To cater the demand, hydroelectric power plants are running under unfavorable conditions such as under high silt content. High silt content in the water leads to extensive material removal from various components of hydraulic machinery. In particular, various components associated with hydro machinery such as turbine blades, labyrinth seals and guide vanes are on the extent of maximum damage by abrasive particles [2]. Slurry erosion in hydro power plant is a major concern, particularly in the hydropower plant which are feeded from tributaries originating from Himalayan region, where during rainy season silt content increases in the water (up to 10000 ppm) passing through the turbines [3]. Hydro power plants which are affected by slurry erosion damage in India are Chameri, Maneri Bhali–I, Nathpa Jhakri, Koteshwar and Dehar where amount of damage is very high and it needs break down after every one or two monsoons. This has resulted in huge monetary loss, reduced effectiveness, forced outages and repair to the hydro power station situated in the Himalayan region [5]. Therefore it is necessary to identify the erosion mechanism of material which causes degradation of material and measures by which it can be prevented.

Erosion is a phenomenon which generally occurs due to the impingement of the hard particles (peebles, sand stone, mud, clay etc.) and liquid mixture generally known as slurry on the surface of the components which it impacts and causes wear marks on the surface which leads to degradation of the material. Abrasive wear occur due to abrasion primarily depends upon the tribological properties of the material exposed to the fluid and on the mechanical properties of solid particles comprises within the fluid [6]. The erosive wear on a surface is governed by the velocity of erodent particles relative to the target surface and impact angle of the striking erodent particles. As depicted from the studies of various researchers that erosive wear is a function of several parameters such as morphology of the solid particles, hardness, concentration, quantity and impact velocity of particles, in most cases, which is minimized by controlling the mentioned parameters or indirectly by controlling impact energy [7-9]. Impact energy of the particle depends upon the size and kinetic energy of particle striking the surface. Fluid feeded to the hydropower plant is generally filtered upto the size of 250 micron, in spite of this, considerable surface damage to hydroelectric machine and structure occurs when ever these high velocity erodent particles impinges on the surfaces, thereby causing wear marks and material removal. It has been learnt from the previous investigations that stainless steels are widely accepted material used in hydro power plants as it owes good corrosion properties and high resistance to solid particle erosion.

Gupta et al. [10] conducted erosive wear test using a slurry pot tester and reported the equation related to volume loss by erosive wear from experimental data:
$E_w = KV^{\alpha}d^{\beta}C^{\gamma}$ Where E_w is erosion rate, V is the impact velocity of the fluid, d is the solid particle size, C is the slurry concentration and K, α, β and γ are the constant values which depends upon the properties of erodent as well as of target material.
It has been learnt from the various investigations of the researchers that slurry erosion resistance of the hydraulic machinery can be improved by the application of thermal spray coatings. The thermal spray coatings may have a high erosion resistance depending upon the surface preparation prior to deposition, chemical and mechanical behaviour of the material deposited and the conditions of various parameters related to deposition. Thermal spraying refers to processes which uses chemical or electrical energy to melt the particles of a powder which are then further accelerated towards the surface of substrate so that it get deposited on it. Thermal spraying is one of the most effective and prominent hard facing techniques used for prevention of substrate from adhesive wear, erosive wear, abrasive wear, corrosive and surface fatigue as caused by the conditions under which material is used. Thermal spraying is a technique in which properties of substrate will be improved by using coating processes in which particles were deposited on the surface in either molten or semi molten conditions to form a layer. Now a days, thermal spray Coatings are widely used in various applications which includes components of automotive system which faces wear and tear, bio materials, thermal power plants components, hydro power plants equipment, chemical industry, aviation industry, pulp and paper processing industry, bridge structures and concrete reinforcements, bio medical devices, land-based and marine industry etc [1]. The powder which is used for depositing coating is available in the form of solid or semi solid material such as powder, ceramic rod, wire or molten materials. Now a days variety of thermal sprayings techniques are available and choosing among them depends upon functional requirements, adaptability of coating material for the intended application technique, level of adhesion required, morphology of the substrate, availability, economic viability.

Bitter [11] proposed two theories of erosion wear phenomenon namely, cutting and deformation, assuming that the wear at any impact angle of solid particle is the sum total of these two wear components. It was stated that at small impact angles the cutting wear prevails which is caused by the particle velocity component parallel to the target surface whereas at large impact angles wear due to repeated deformation prevails due to the normal component of the velocity. Some researchers depicted that hardness of the target material and hardness of the erodent's plays a significant role in erosive wear.

It was observed that surface hardening of the target material plays a role in controlling the erosion process. The scanning electron microscope studies of worn surfaces revealed various wear mechanism such as micro ploughing, lip formation, platelet, small craters for indentation and micro cracking. It has been found that for ductile materials such as metal and alloys, material removal is caused by micro cutting and micro ploughing of solid particles. For brittle materials such as ceramics, the cracks coalescences will lead to large scale material removal. This process will induce the material deformation, crack initiation and propagation. As a result the material pieces detach from the surface.

Desale et al. [12] investigated normal impact wear of seven different ductile material using different erodent namely quartz, silicon carbide and alumina. The researcher observed that erosion wear of ductile materials at normal impact condition was a function of the ratio of erodent hardness to target material hardness further they found that erosion rate remained constant for range of hardness ratio. In this investigation three regions of hardness ratio were identified as 4.2-5.2, 6.9-12.1 and 12.5-27.5. Erosion rate varied in the narrow range within the regions owing to the effect of parameters other than hardness ratio.

Keeping in view of the versatility and in situ application possibilities along with comparison of thermal spray coatings as given in Table I., the HVOF thermal spray process has been choosen for in depth review in the current paper. The process has been reviewed with regard to its application in prevention of slurry erosion in hydraulic power plant which is the main focus of this Paper.

Table 1: Comparison of various thermal spray processes

Deposition technique	**Heat source**	**Propellant**	**Typical temperature (^{o}c)**	**Typical particle velocity m/s**	**Average spray rate kg/h**	**Coating porosity % by volume**	**Relative bond strength**
Flame spraying	Oxy acetelene/ oxy hydrogen	Air	3000	30-120	2-6	10-20	Fair
Plasma spraying	Plasma arc	Inert gas	16000	120-600	4-9	2-5	Very good
Low plasma spraying	Plasma arc	Inert gas	16000	Up to 900	-	<5	Excellent
Detonation gun spraying	Oxygen/acetylene/ Nitrogen gas detonation	Detonation shock waves	4500	800	0.5	0.1-1	Excellent
High velocity oxy fuel	Fuel gases	Combustion jet	3000	800	2-4	0.1-2	Excellent

HVOF Thermal Spraying (High Velocity Oxygen fuel)

Among the commercially available thermal spray coating techniques, High Velocity Oxy Fuel (HVOF) spray are among the best choices to attain hard, less porous and wear resistant coatings [3]. In this process relatively low temperatures and high kinetic energy (>1000 m/s) are used which resulted into interlocking of semi molten particles with each other and it leads to increase in the cohesive strength of the particles. The resulting coating has low porosity and high bond strength. Adhesion between the coating and substrate for a HVOF spray coated substrate can be 10 times higher than those from other flame spraying processes. HVOF thermal spray technique is known as dry process technique that uses a dense metal coating whose desired physical properties are equal to hard chrome plating (HCP). These properties include high resistance to fretting fatigue, Erosion resistance, low residual stress, low residual stress thermal behavior, prone to corrosion, lesser oxide content, lower porosity and higher bond strength. HVOF process uses the combined effect of kinetic energy and thermal energy i.e. melting of the powder particles and transfer of powder particles on to the substrate. Powder particles of the desired coating material are fed axially into emanating hot gas stream, which is further feeded into a spray gun, where they are melted and propelled to the surface of the work piece to be coated.

The HVOF spray system consists of a spray gun, powder feeder unit, flow meter unit, air and gas supply unit. Schematic view of HVOF spray gun is shown Fig. I. In this process mixture of gaseous or liquid fuel and oxygen is supplied into a combustion chamber, where it will ignite and combusted continuously. As a result of combustion, hot gases are emanated at high pressure which further goes through a converging–diverging nozzle and further travelled through a straight section. The fuels can be gases (hydrogen, methane, propane, propylene, acetylene, natural gas, etc.) or liquids (kerosene, etc.). The velocity of the gas jet which emanates through the outlet of the barrel (>1000 m/s) exceeds the speed of sound. Powder feed stock is further injected into the gas stream which is at high velocity, it further accelerate the powder up to 800 m/s. This accelerated powder is further impacted on the substrate where coating has to be deposited. This powder partially melts in the stream and partially on the deposited surface due to the impact of powder particles at high velocity upon the substrate. Due to the heat generation during impact of particles on the substrate, particles get fully molten to form high quality HVOF coatings. As a result of which they are interlocked with each other and produced quality coatings.

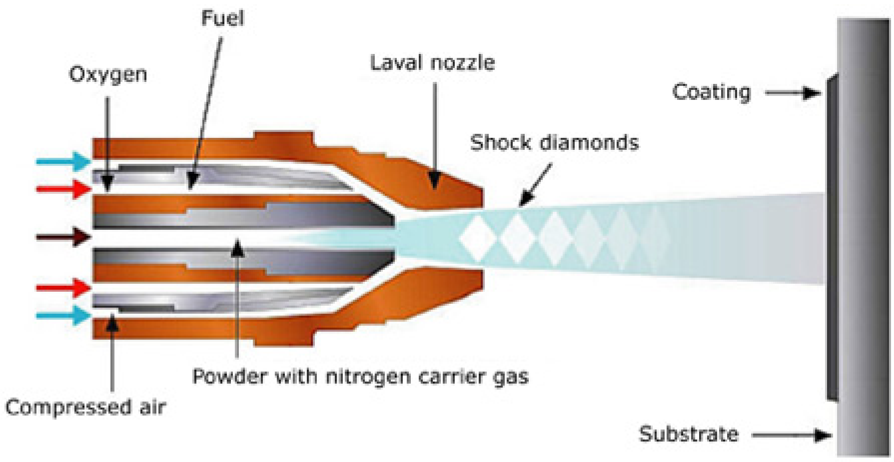

Fig. 1*:* Schematic Diagram of the HVOF Process [13]

HVOF coatings offers good bond strength, relatively lower porosity and high density which leads to high mechanical strength, high hardness and good toughness in the material, which makes it able for application in aggressive environments such as higher temperature, erosive and corrosive environment.

Studies related to Erosive behaviour of HVOF sprayed coatings

A comprehensive literature survey of various HVOF-sprayed coatings with respect to their performance under slurry erosion conditions has been reported in this section. The same has also been summarized in the Table II so as to serve it as ready recknor for the readers. Further in depth studies of work done by the various investigators are explained in subsequent paragraphs.

Table 2: Ready recknor of the research work done by various researchers on the use of HVOF sprayed coatings to improve slurry erosion resistance of the material

Authors	Base material	Coating	Test rig	Erodent	Results/conclusion
Peat et al.	S355 steel	WC-CoCr, Cr_3C_2-NiCr and Al_2O_3	Liquid impingement test rig, dry erosion test rig	Alumina with an average particle size of 50 μm	• Under the both cases of dry erosion and slurry erosion conditions Cr_3C_2-NiCr exhibited the maximum volume loss out of all examined coatings. • WC-CoCr shows significant reduction in volume loss and wear scar depth at an impingement angle of 20^o in comparison with Cr_3C_2-NiCr and $Al_2O_{3.}$ It was attributed with high coating hardness and retention of hard carbide particles in cobalt matrix.
Taillon et al.	Martensitic and Ferritic Stainless Steels	Pure Fe3Al powder and Fe3Al reinforced with nitride and boride phases HVOF coatings	G32 vibratory setup.	Cavitation erosion	• Martensitic stainless steels present lower erosion rates and longer incubation periods than ferritic steels as a result of micro hardness. • Cavitation erosion mechanisms of steels are crack formation followed by material removal. Ferritic steels presented cracks at grain boundaries and in the grains themselves. • Fe3Al based metal–ceramic coatings showed similar erosion rates to other studied HVOF coatings sprayed from commercial powders, WC–CoCr and Cr3C2–NiCr.
Peat et al.	S355 steel	Tungsten Carbide, Chromium Carbide and Aluminium Oxide	Recirculating liquid impingement test rig	slurry erosion-corrosion	• Reported erosion as dominating factor for degradation of material. it was pointed out that corrosion contributes for only 6% of the total mass loss in case of uncoated S355. • Higher mass loss was exhibited by Cr3C2-NiCr coatings due to the large carbide size particles. • Al2O3 reported to be highest eroded coating and it was attributed with lack of ductile binder as a result of which rapid removal of alumina particles takes place which acted as a secondary erosive medium within the slurry, resulting in enhanced mass loss.

					• WC-CoCr reported to be the best coating associated with higher hardness.
Thakur et al.	Multi-walled carbon Nano tubes (MWCNTs)	Nano-WC-CoCr coating	Jet-type slurry erosion test rig	filtered water and silica sand (SiO2) particles	• Reported powder particle size as the major contributor enhancing erosion performance of WC-Co based coatings. Reported micro cutting and ploughing at 30° impingement angle of CoCr matrix, resulting in loosening and pull-out of WC grains. In case of 90° impingement angle test, the material removal due to fracturing of WC grains and eruption of CoCr matrix by interlinking of cracks.
Kumar et al.	23-8-N nitronic steel	WC–10Co–4Cr	air jet erosion tester	Flaky and angular alumina particle of 50 µm size	• Reported improved erosion resistance at both impact angles. Solution treatment of the samples prior to coating enhanced fracture toughness along with insignificant reduction in hardness of the coating.
Ciubotariu et al.	Martensitic 13-4 Stainless steel	Stellite 6 layers	Cavitation erosion tester	Cavitation	• Reported HVOF to be the best method for protection against Cavitation Erosion. • Laser remelting carried out for improvement of the coating structure and to enhance intimacy with base material of the component.
Praveen et al.	AISI 304	NiCrSiB–35 wt%WC–Co	Hot air jet dry erosion test rig	Alumina particles of average size 50 µm	• It was reported that coating exhibited ductile erosion mechanism proved to be a better erosion resistant. Erosion resistance of the coating is twice at impingement angle of 90o in comparison with 30o impact angle. • Optimum values for least erosion was predicted as 220 lpm of oxygen flow rate, 65 lpm of fuel flow rate, 28g/min of powder feed rate and 300 mm stand off distance.
Hong et al.	Stainless steel 1Cr18Ni9Ti	WC–10Co–4Cr	Vibratory Cavitation apparatus	3.5 wt.% NaCl solution	• Coating exhibited dense structure and low porosity. • Coated samples exhibited higher cavitation erosion resistance in comparison with stainless steel 1Cr18Ni9Ti. •
Goyal et al.	CA6NM Turbine Steel	Cr3C2–NiCr	Slurry erosion	Silica particles	• Hardness depicted as major factor attributed in increasing slurry erosion resistance.

					• Reported velocity as major contributor in increasing erosion rate followed by particle size and slurry concentration.
Goyal et al.	CF8M and CA6NM Steels	Cr_2O_3	Slurry erosion	Silica particles	• Rotational speed as a dominating factor leading to higher erosion rates. • Coating provides higher hardness which leads to lower erosion rates.

Dry and slurry erosion analysis of three HVOF-sprayed coatings namely WC, Cr_2C_3 and Al_2O_3 deposited on S355 (EN: 10025) was done by **Peat et al. [14].** The erosion test were conducted at an impingement angle of 20^o.The dry and slurry erosion tests were conducted using dry erosion and slurry erosion test rigs, as shown in Fig. II and Fig. III respectively. In dry erosion tests, alumina particles of 50 μm size impacted the target surface from a standoff distance of 100 mm at a feed rate of 5.3 g/s. In slurry erosion test, the erodent particles consist of sand particle with an average size of 0.355mm impacted the target surface at an impingement velocity of 24m/s.

The researchers observed that the erosion resistance of the HVOF-sprayed coatings is directly related to their hardness as shown in Fig. V. Further, it was found that the density and hardness of coatings produced by HVOF-spray technique are much better than the same obtained by other thermal spray processes. To compare the behaviour of various coatings under dry and slurry erosion conditions, the plots of total mass loss from each coating have been shown in Fig. IV respectively. The researchers also revealed that coating micro structural integrity, composition and hardness were the major determinants of relative erosion resistance of coatings in all tests, with matrix corrosion resistance influencing the surface damage resistance of cermets.

In order to mitigate the effect of the corrosion under Slurry erosion testing regime, cathodic protection was provided. It was also proved that any damage to the surface could be attributed to pure erosion and as such, be assessed against the dry erosion test data. To identify the mechanism of failure of the coatings, the researchers analyzed the SEM images of eroded surfaces and observed that impinging slurry results in wear scars over the surfaces. Results obtained after testing revealed variation in the level of degradation experienced by each type of coating under the respective test conditions. It was found that Tungsten Carbide with a Cobalt binder gives the best result for both cases of dry erosion and slurry erosion testing. Researchers also established the relation between hardness and with thickness of the coating as shown in Fig. VI. It was observed that hardness of the coating increased with thickness of coating up to some critical value and it started to decreasing with increase in thickness of coating. The same has been shown in the Fig. there is general perception that hardness of coating increases with increase in thickness. However in the present study the decrease in hardness with increase in thickness may be attributed to the weaker attachment of the particles with each other.

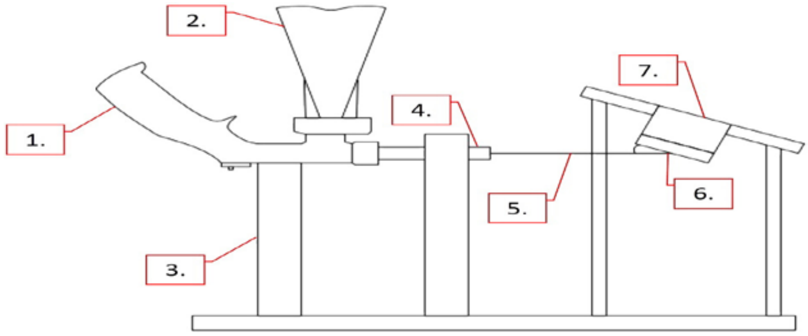

Fig. 2*: Schematic view of dry erosion test rig [14]*

(1) Sand blasting gun (2) Particle hopper (3) Rig fixture (4) Jet nozzle (5) Particle stream (6) Sample (7) Auxiliary electrode

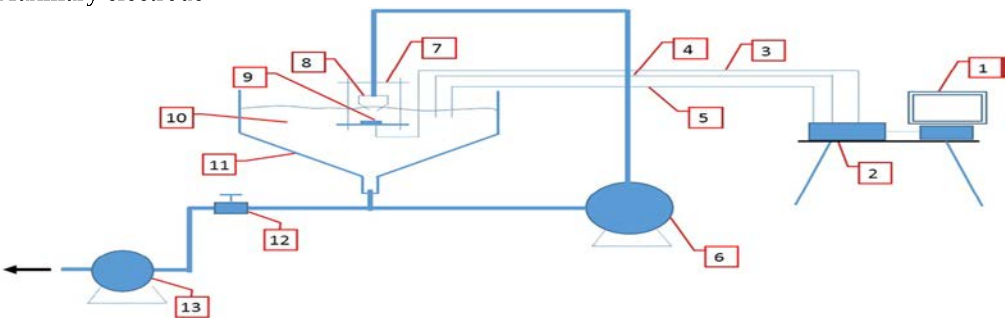

Fig. 3: Schematic view of recirculating liquid impingement test rig [14]

(1) Data control unit (2) Potentiostat (3) working electrodes (4) Reference electrode (5) Sample holder (6) Recirculating pump (7) Sample holder (8) Nozzle (9) Specimen (10) Slurry (11) Slurry tank (12) Drainage valve (13) Drainage pump.

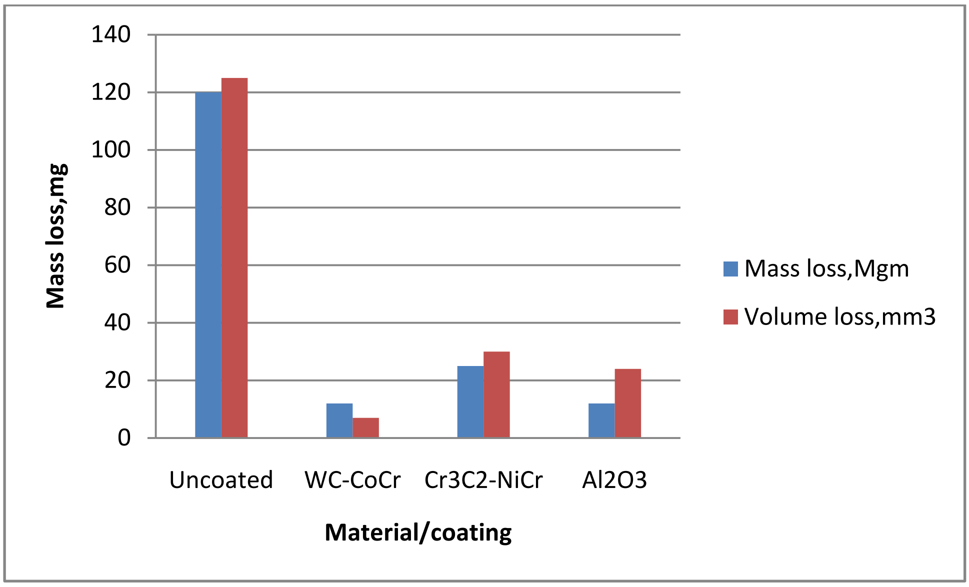

Fig. 4: Erosive rate loss under dry erosion testing regime [14]

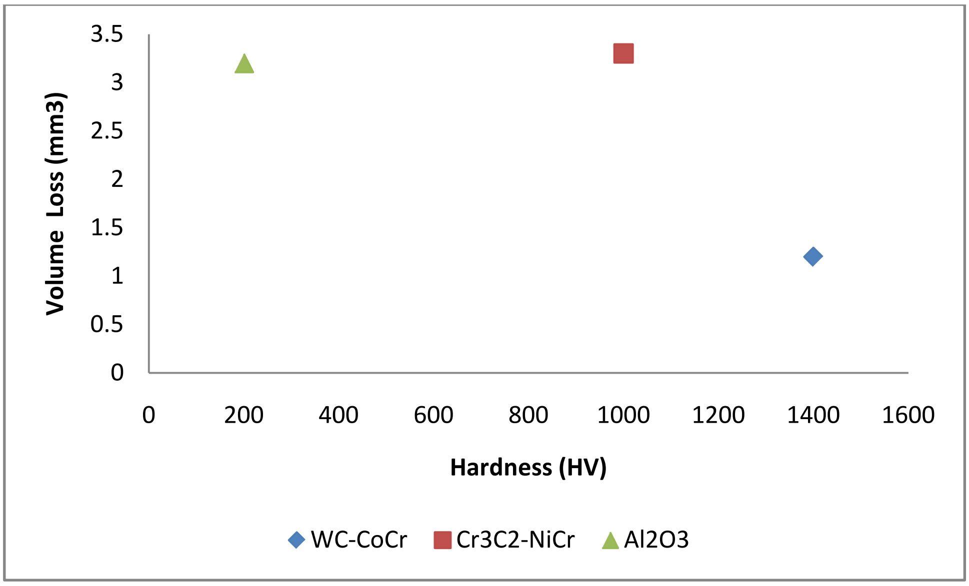

Fig. 5: Volume loss with respect to coating hardness under slurry erosion test regime [14]

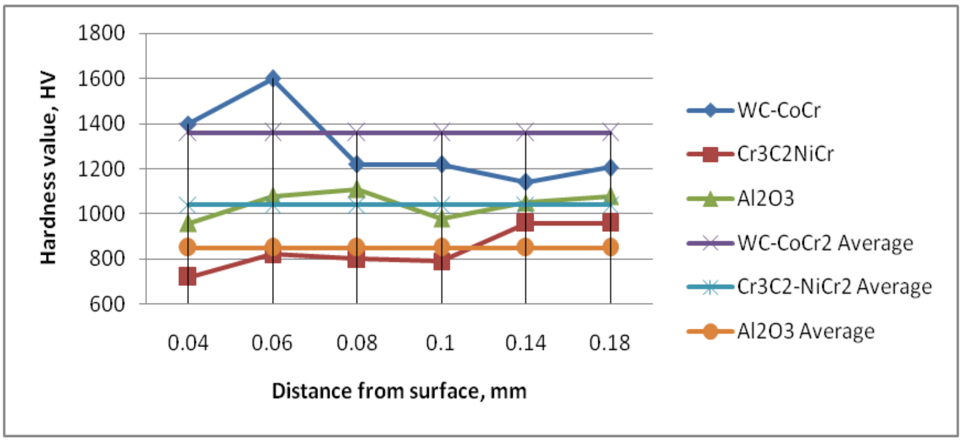

Fig. 6: Relationship between coating hardness and distance from surface [14]

Similar studies to ascertain the cavitation erosion behaviour of hydraulic machinery were carried out by **Tailon et al. [15].** In the study, erosion behavior studies of various steels such as 13Cr-8Ni (S13800), 13Cr-4Ni (S41500), 15Cr-5Ni (S15500) and AISI 1018, ferritic AISI 444 steels and HVOF-sprayed Fe3Al (pure and reinforced with nitride/boride phases) coatings were carried out by using the G32 vibratory setup. To evaluate the change in the performance of given steels after deposition of the HVOF-sprayed coatings under cavitation erosion environment, comparison of erosion rate was made between the uncoated and above mentioned HVOF-sprayed coated low carbon and soft martensitic stainless steel specimens. In order to assess the effect of hardness on cavitation erosion resistance, various mechanical properties were evaluated by using depth sensing indentation as given in the table III. It was found that HVOF-sprayed coatings exhibited lower erosion rates than martensitic stainless steels. Generally it is observed that higher hardness is associated with better erosion resistance, however, in this study it was found that higher hardness for steels followed the fact, but the same was not true in the case of the HVOF-sprayed coatings. It was concluded from the study that cavitation erosion resistance of coatings does not correlate with hardness (H), young modulus (E) of the coating, porosity or matrix fraction. From SEM images, it was depicted that the ceramic particles seem to be removed once the metal matrix surrounding it is eroded. Defects, porosity or particle boundaries might have acted as crack nucleation sites.

Table 3: Showing mechanical properties of steel and HVOF Coatings [15]

Bulk Steel	H [GPa]	E [GPa]
13Cr–8Ni (S13800)	5.5±0.2	248±10
13Cr–4Ni (S41500)	4.1±0.3	235±11
15Cr–5Ni (S15500)	5.0±2	246±15
AISI 444	2.5±0.2	248±13
1018	2.1±0.2	245±15
WC–CoCr	14.5±3.0	281±33
Cr3C2–NiCr	11.4±2.0	214±14
Fe3Al (milled)70–10	4.6±0.9	131±13
Fe3Al (unmilled)	3.1±.6	108±17
(Fe3Al)30Ti35BN35	12.5±.6	222±16
(Fe3Al)30Ti35BN351400 °C	9.0±1.4	196±17

The investigation of slurry erosion behaviour of conventional and nano sized WC-10Co-4Cr powders deposited by HVOF-spray process was done by **Thakur et al. [16].** The conventional WC-10Co-4Cr (CWC) powder composed of WC grains of size 2–5 μm, whereas the nano structured WC-10Co-4Cr (NWC) powder consisted of carbide particles of size 50–500 nm mixed with multi-walled carbon nano tubes (MWCNTs). Slurry erosion testing was performed by using Jet-type slurry test rig using SiO_2 particles of size of 100-300 μm as erodent. The experiments were conducted at an impact velocity of 18.5m/s and impingement angle of 30^o & 90^o. To correlate the micro structural behaviour with erosion mechanism various coating properties such as porosity, micro-hardness, surface roughness and indentation fracture toughness have been measured. To characterize and identification of failure mechanism, scanning electron microscopy (SEM) images of thermal spray powders, deposited coatings and worn-out surfaces has been investigated. The erosive wear results of eroded obtained by the authors are shown in Fig. VII. The worn-out surfaces revealed that the material has been removed due to micro-cutting and ploughing of CoCr matrix, resulted in loosening and pull-out of WC grains in case of 30° impingement angle during erosion testing. Further testing at normal impingement angle revealed fracturing of WC grains followed by eruption of binder matrix by interlinking of cracks originated from fractured WC grains. Splat bridging feature of the MWCNTs improved the fracture toughness of nano-WC-CoCr coating. Researcher revealed that introduction of MWCNTs favoured the plastic deformation around the bridging which resulted in suppressing the brittle fracture of coating material. The increase in fracture toughness further resulted in enhancement of erosion resistance of MWCNTs modified nano WC-CoCr coating.

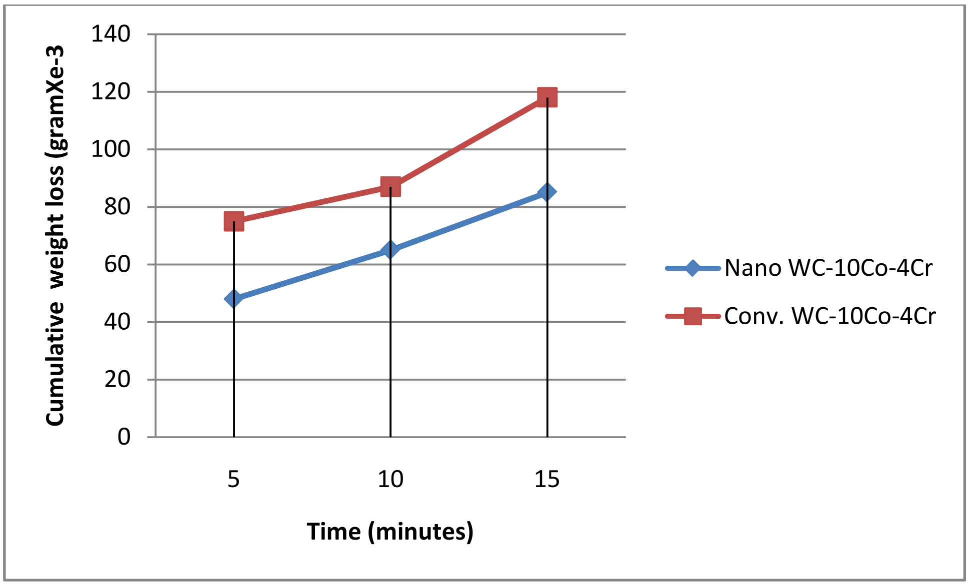

Fig. 7: Cumulative weight loss w.r.t time [16]

The effects of average particle size of slurry, slurry speed and slurry concentration on slurry erosion behaviour of HVOF sprayed 75Cr_3C_2-25NiCr and Cr_2O_3 on CA6NM grade of ASTM 743 steel was investigated by **Goyal et al. [17-18].** Tests were conducted on wide range of parameters comprises two levels of speed, average size of slurry particles and slurry concentration by using High speed erosion test rig (TR401, Ducom, India). Erosion rate w.r.t various parameters such as rotational speed, average particle size and slurry concentration was obtained] after testing. It has been depicted that slurry erosion resistance of Cr_2O_3 coating was maximum, it was attributed with higher hardness as compared with Cr_3C_2-NiCr and CA6NM steel which induces lesser erosion rate of material. It was further revealed that rotational speed act as dominant factor in slurry erosion process. It was found that with increase in rotational speed erosion rate increases as shown in Fig. X, it was associated with the higher impact velocity due to increase in rotational speed. It was concluded from the study that the erosion rate is directly proportional to the kinetic energy of impacting particles.

It was also observed that with increase in average size of particle, erosion rate increases further as shown in Fig. VIII. It was attributed with increase in kinetic energy of impacting particles. It was revealed that the effect of increase in slurry concentration was more dominant in case of CA6NM steel than HVOF sprayed coating as shown in Fig. IX. further it was observed that with increase in slurry concentration same amount of erosion rate will not increases as seen in the earlier range of slurry concentration, Authors attributed it with the fact that at higher slurry concentration, only a portion of particles are actually impacting on the target surface, while other loose their way to the target surface due to multiple particle collision among themselves. To predict erosion mechanism, various characterization techniques, such as SEM and XRD was used. It was observed that in case of steel erosion was due to crater and lip formation, plastic deformation, cutting and ploughing, where as for Cr_2O_3 it was micro chipping at splat boundaries and removal of protuberances from the surfaces.

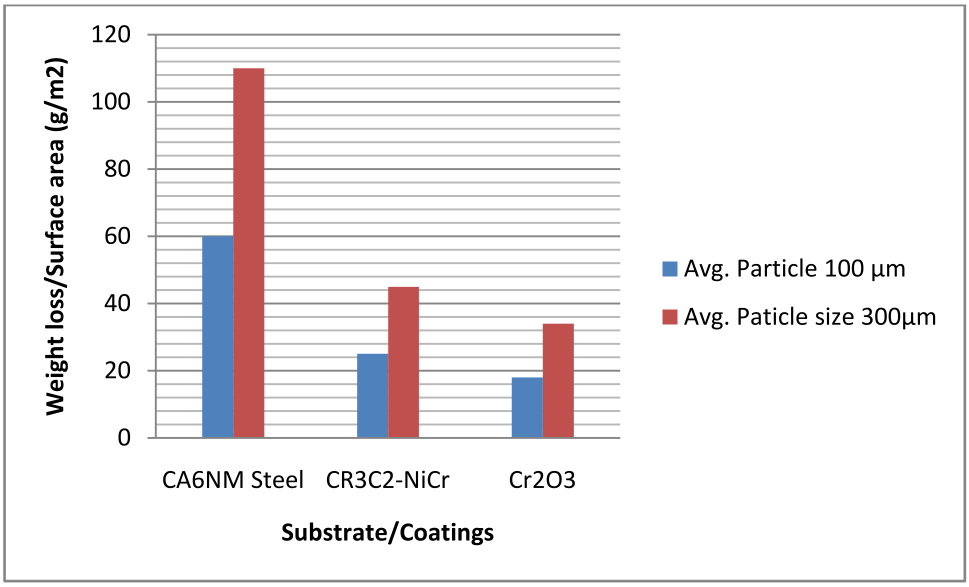

Fig. 8: Effect of particle size on erosion rate of uncoated and HVOF coated CA6NM steel [17-18]

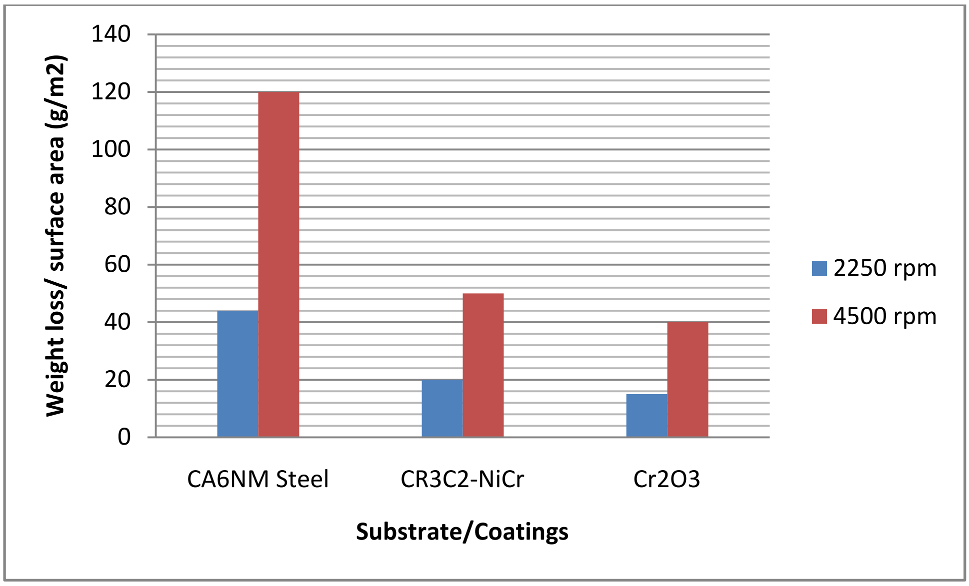

Fig.9: Effect of impact velocity of impacting particles/rotational speed of rotor on erosion rate of uncoated and HVOF coated CA6NM steel (17-18)

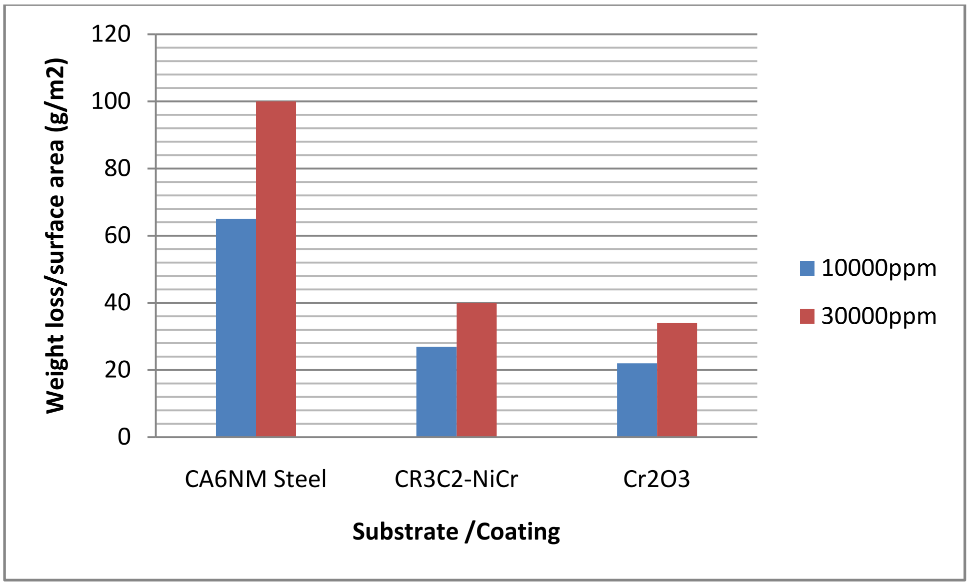

Fig. 10: Effect of concentration on erosion rate of uncoated and HVOF coated CA6NM steel [17-18]

Similar kind of study on the erosive and abrasive wear behaviour of HVOF deposited WC-12Co, WC–10Co–4Cr and Cr_3C_2−25NiCr coatings was investigated by **Vashishtha et al. [19]**. It was found that the maximum wear rate was exhibited by Cr_3C_2−25NiCr coating under both testing regimes i.e. solid particle erosion and abrasion testing regime. The coatings exhibited composite erosion response under the testing conditions. It was further associated on the basis of velocity exponents, erosion mechanisms and mechanical properties. It has been concluded that erosion damage parameter and severity of contact, predicts the transition in failure modes. It was further analyzed that the wear mechanism was mainly influenced by the test conditions and microstructure of the coatings, wear in coatings carried out due to fracture and pull out of carbides, removal of splats and subsurface cracking. The lowest coefficient of friction exhibited by Cr_3C_2−25NiCr coating was attributed due to the formation of tribo oxide film.

The erosion behaviour of WC–10Co–4Cr coating, deposited by HVOF sprayed process on cast and solution treated (1220 $^{\circ}$C/150 min) 23-8-Nitronic steel substrates were examined by **Kumar et al. [20]**. Erodents of alumina particle with 50µm size having flaky and angular type shape has been used on air jet erosion tester at two different impact angles (30° and 90°), velocity of 60m/s and erodent feed at 2.5 g/min have been used for evaluation of erosion resistance. It has been observed that substrate treated with the solution resulted in higher toughness, ductility and impact energy with insignificant reduction in hardness as compared to cast substrate. Erosion rate obtained with both impact angles at 30^{o} and 90^{o} were presented in Fig. XI. For predicting the mechanism of erosion, various characterization techniques such as X-ray diffraction (XRD) analysis and field-emission scanning electron microscopy (FESEM) were applied on the as-coated and eroded surfaces. It was revealed that coating sprayed on the solution treated substrate was better in comparison to the cast substrate due to highly dense and well-compacted structure with lesser porosity, decarburization and inter-splat oxidation. High fracture toughness and hardness of coating along with optimum mechanical properties resulted in higher erosion resistance. It was further revealed by using FESEM analysis that erosion behaviour of WC–10Co–4Cr coating was fully dependent on the relative size of the crater formed with respect to the WC grain size. It was observed that the combined mode of ductile and brittle erosion has been responsible for degradation of the

Coating. It was concluded that such treatment with solution affect the deposition efficiency and erosion behaviour of the coating.

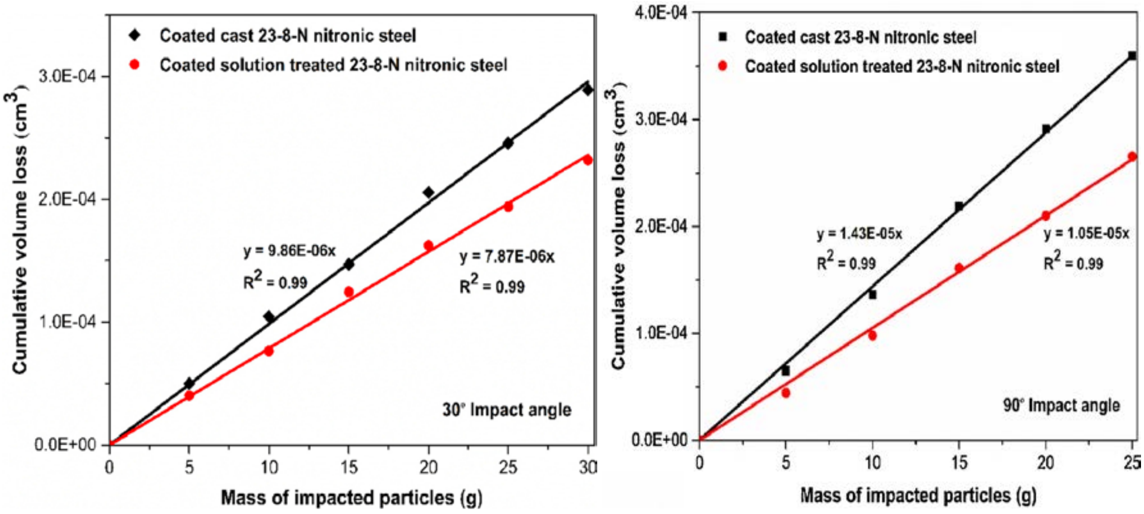

Fig.11: Erosion rate variation with impact angles [20]

To correlate the erosive wear performance with composition and microstructure **Hawthorne et al. [21]** examined 10 HVOF cermet and metallic coatings under both slurry jet and dry particle jet environment. For assessment of the erosion behaviour, Slurry jet erosion testing was carried out by using re-circulating loop apparatus which consist of 9 wt. % alumina in water as slurry with size of 35 mm and 200 mm angular shaped particles, at an impact velocity of 15 m/s and flow rate of 18 lr/min were used. Dry particle erosion was carried out with 50 mm diameter alumina particles at an impact velocity of 84 m/s and feed rate of 2 g/min. it was observed that dry erosion rate was higher in magnitude in comparison with slurry erosion rate as shown in Fig. XII and Fig. XIII. It was attributed with the difference in actual particle size and target impact velocities in the respective test regimes. For all erosion resistance tests, major determinants of relative erosion resistance were coating composition, micro structural integrity and hardness. Further it was revealed that matrix surface damage resistance was directly influenced by the corrosion resistance of cermets which are used under prolonged water slurry conditions. It was also observed that target material hardness plays an important role in providing resistance to the material. It was revealed that in absence of corrosion, the ranking of the 10 HVOF coatings with respect to slurry erosion resistance was same at 90^o or 20^o impingment angle. It was further reported that the WC–12Co cermet coating was more prone to erosion–corrosion damage in aqueous slurry testing than that of the WC–10Co–4Cr matrix coating.

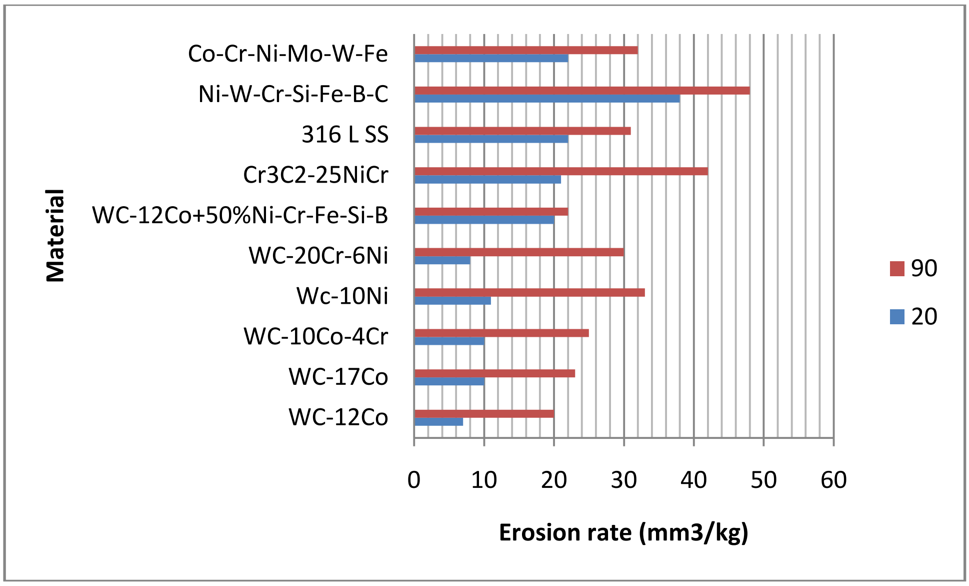

Fig. 12: Dry erosion results for 50 mm particles at two impingement angles for 25 min exposure [21]

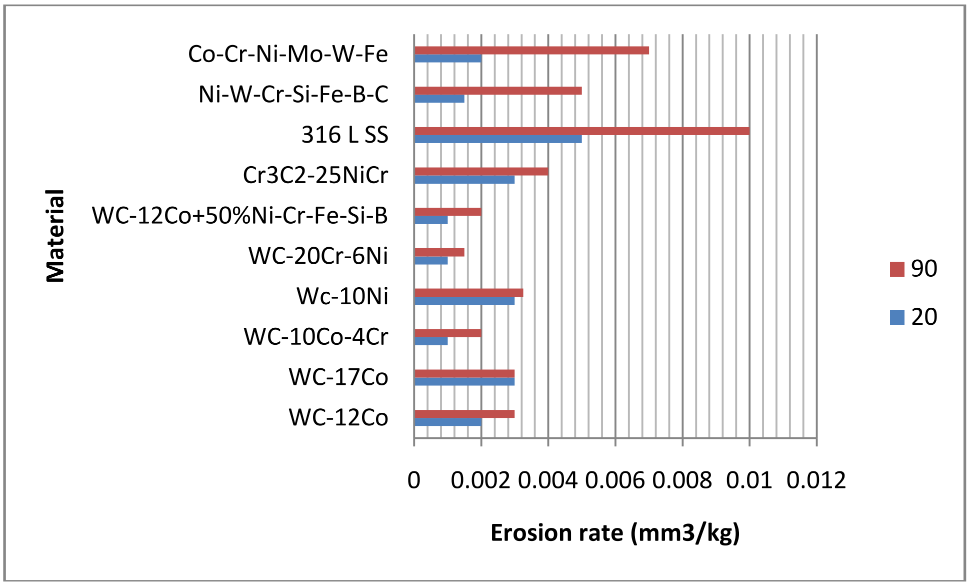

Fig. 13: Erosion rate for different coatings using 35mm particles at different impingement angles for 4 h exposure [21]

Similar studies by **Hong et al. [22]** investigated the synergistic consequence of HVOF deposited conventional WC–10Co– 4Cr coatings and FeCrSiBMn amorphous/ nano crystalline coatings on the cavitation erosion resistance of the both coatings. It has been reported that the WC–10Co–4Cr coating resulted in better cavitation erosion resistance in comparison with FeCrSiBMn coating. The results in terms of cumulative volume loss w.r.t time were reported as shown in Fig. XII. It was observed that after eroded for 30 h, the volume loss rate of the WC–10Co–4Cr coating was about 2/5th that of the FeCrSiBMn coating. It has been revealed that cavitation erosion played a key role in erosion of both the coatings. While analyzing the total cumulative volume loss rate it was revealed that the total contribution of the erosion in WC–10Co–4Cr coating was higher in comparision with

FeCrSiBMn coating. It has been revealed that mechanical effect acted as a major factor which affected the cavitation erosion behavior of both the coating.

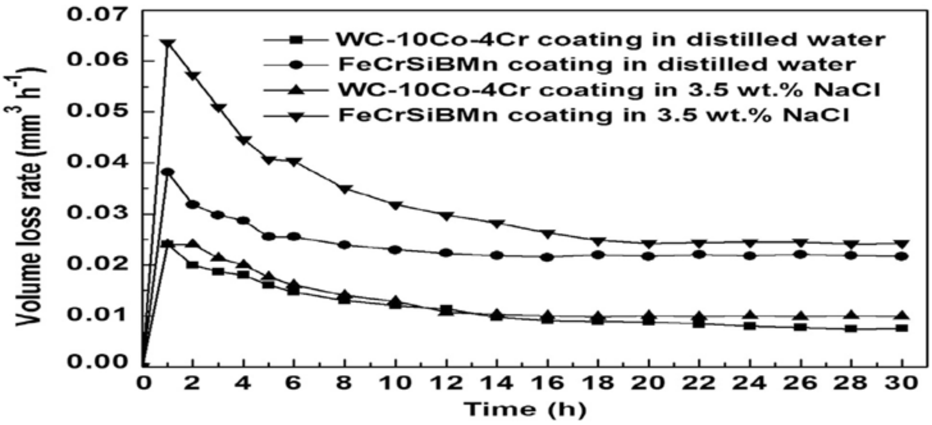

Fig. 14: Cumulative volume loss rates as a function of time for different coatings under cavitation erosion [22]

To identify the optimum spray parameters for carrying out HVOF sprayed process **Praveena et al. [23]** investigated the effect of range of parameters by using Taguchi approach to determine higher erosion resistance at an impact angle of 90^o. Various spray parameters such as oxygen flow rate, fuel flow rate, powder feed rate and standoff distance were optimized by using above said technique. The Standoff distance and powder feed rate were identified as the major contributor which leads to higher erosive wear loss. The important sequence of the spray parameter was revealed according to their impact on erosive wear. It was reported that standoff distance has maximum impact on erosive wear and oxygen flow rate as the least one. 65 wt% NiCrSiB–35 wt% WC–Co coatings was develop665ed on AISI 304 stainless developed based on the optimum parameters obtained from the study such as 220 lpm oxygen flow rate, 65 lpm fuel flow rate, 28 g/min powder feed rate and 300 mm standoff distance and erosion testing was carried out. It was revealed that the optimum condition produces minimum erosion wear loss. Based on the optimum parameters attained by using Taguchi approach, high velocity oxy-fuel (HVOF) thermal spraying was developed. To give further insight of the microstructure of the optimized coating, Scanning Electron Microscope (SEM) equipped with Energy dispersive spectroscopy (EDS), Optical microscope (OM) and X-Ray Diffraction (XRD) was used. To correlate the erosive behaviour with the coating properties micro hardness, porosity and surface roughness of the coating were measured. Erosion wear testing of the optimized coating was conducted at 30^o, 60^o and 90^o impact angle by using hot air jet erosion testing machine and results of the investigations are shown in Fig. XIII. To predict the erosion mechanism of the erodent samples, SEM were further analyzed. It was pointed out that coating comprises splats, mixture of partially melted and unmelted particles in the form of globules and voids or pores which are known as to be the typical structure of thermal spray coatings.

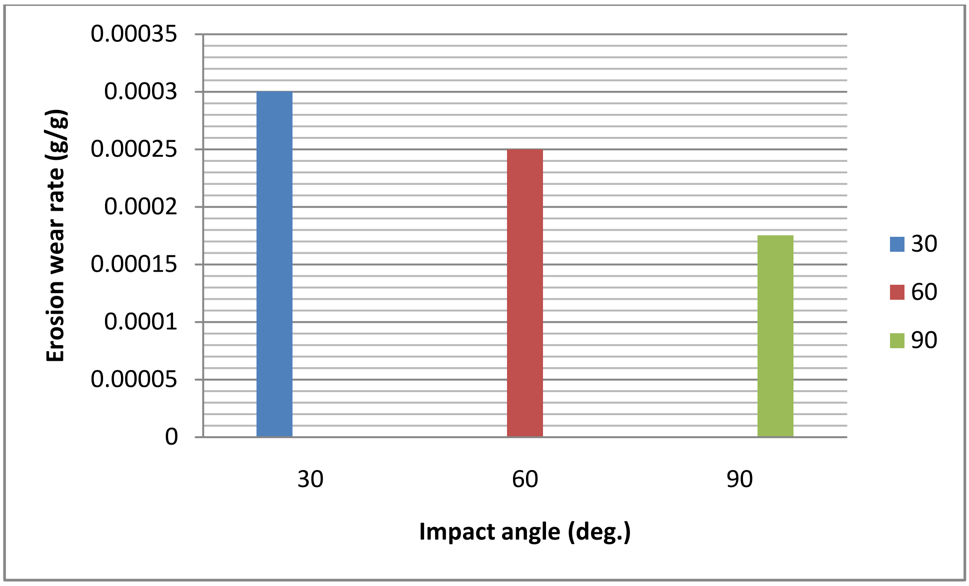

Fig. 15: Erosion rate with respect to optimum parameters determined by using Taguchi Technique [23]

With an aim on identification of the contributing factors which leads to erosion, corrosion and synergy **Peat et al. [**24] carried out comparative study of three HVOF sprayed coatings, Tungsten Carbide, Chromium Carbide and Aluminium Oxide, under slurry erosion-corrosion conditions. The main focus was for the identification of the parameters which causes coating degradation. For providing insight applied electrochemistry as well as metallographic analysis has been used to evaluate the degradation mechanism. Extensive experimentation was further carried out to analyze the performance of the mentioned coatings under erosion-corrosion conditions which represented an actual flow environment. It was further predicted that the breakdown of Chromium Carbide and Aluminium Oxide coatings resulted in enhanced mass loss in comparison with uncoated S355 steel. Results of experimentations revealed that Tungsten Carbide with a Cobalt binder acted as an effective coating which resulted in significant decrease in total material loss incomparison to uncoated S355 steel.

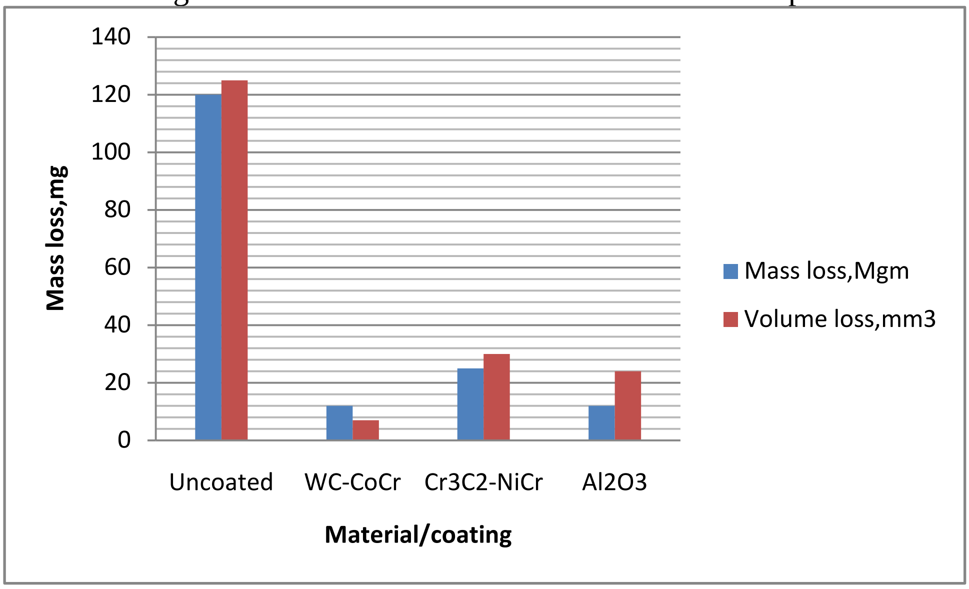

Fig. 16: Average mass and volume loss under dry erosion conditions [24]

To investigate the effect of using different flux in HVOF thermal spray system **Wanga et al. [25]** carried out coating by using two different flux such as 6 and 6.5 GPH kerosene flux, 1850 and 1950 SCFH oxygen flux. Spray parameters such as spray distance of 330 and 380 mm were used for carrying WC-10Co-4Cr coatings by using Parxair JP-8000 HVOF thermal spray system. Influence of flux on the various coating properties such as hardness, crystalline phase, fracture toughness, thickness per pass and abrasive wear resistance has been investigated. It was further observed that kerosene flux, oxygen flux and spray distance have notable effects on coatings microstructure and performance, but only minor effect on the phase of coatings. The hardness of WC-10Co-4Cr coatings considerably increases with the kerosene flux and oxygen flux. Appreciable reduction in wear loss and the fracture toughness was reported with the increasing of coating hardness. It was also revealed that WC-10Co-4Cr coatings exhibited higher wear resistance in comparison to hardening and tempering of steel.

To prevent the brittleness of the stellite coating and to induce higher adhesiveness between the substrate and coating **Ciubotariu et al. [26]** investigated the effect of laser remelting technique. It was well known that Stellite 6 known as cobalt based alloy provides good resistance to wear. In order to develop such coatings by welding and thermal spraying special measures were taken to prevent the brittleness of the coating. To remove this bottleneck remelting technique was applied by using the optimal value of pulse power, which provided a homogenous layer with good adhesion to the substrate. Stellite 6 powder has been deposited by using HVOF thermally sprayed coating on a martensitic 13-4 stainless steel substrate which is generally used for hydraulic machinery components. In order to enhance the adhesion of the coating with the substrate and to improve the microstructure of the HVOF-sprayed coating, laser remelting was applied, using a TRUMPF Laser type HL 124P LCU under a range of working parameters. With the help of light microscopy, microstructures of the coatings under different conditions were analyzed. Further with the help of light microscopy the optimal value of pulse power was predicted which provided a homogeneous stellite 6 layer with good adhesion to the substrate. Further it was revealed that the values of pulse peak power in the range of 1550W were attained during optimization of the laser remelting procedure of the Stellite 6 layer.

Bolelli et al. [27] investigated the High-velocity oxygen-fuel (HVOF) sprayed nano structured WC–10Co–4Cr coating. For analyzing the cavitation erosion behavior and mechanism of the coating, 3.5 wt. % NaCl solution was used. Microstructural analysis by using XRD images shows the presence of amorphous phase and WC grains in the coating. It has been depicted that the cavitation erosion resistance of the coating was about 1.27 times that of the stainless steel 1Cr18Ni9Ti under the same testing conditions. Further investigations regarding the effects of erosion time on the microstructural evolution has been carried out. It has been revealed that cracks initiated at the edge of pre-existing pores and propagated along the carbide–binder interface, leading to the pull-out of carbide particle and the formation of pits and craters on the surface. Erosion of the binder phases, brittle detachment of hard phases and formation of pitting corrosion products revealed as the failure mechanism of the coating.

To investigate the erosion behaviour of HVOF-sprayed WCCo/NiCrFeSiB coatings on GrA1 boiler tube steel **Ramesh et al. [28]** carried out this coating on the above said steel. It has been reported that on depositing HVOF-sprayed coating on substrate, hardness was progressively increased up to $1223HV_{0.3}$. For further insight of erosion behaviour, experimentation was carried out by using air jet erosion test rig according to ASTM G76-02 standard which consist silica particles of size 120-180µm, impact velocity of 40m/s and impact angle of 30^o & 90^o. The results obtained from the testing were shown with the help of histogram as shown in Fig. XV. For characterization of the as-sprayed as well as eroded coatings scanning electron microscope and optical profile meter has been used. It was observed that WCCo/NiCrFeSiB coatings comprises of higher amount of WC in matrix with a minor amount of W2C brittle phase. Further it has been observed that the erosion resistance of WC-Co/NiCrFeSiB coating was attributed with composite mode. Among composite modes of material removal, brittle mode was more dominant. The morphology of the eroded surface pointed out craters, groove formation in binder matrix, lips and platelet formation, and carbide particle pull out as the existing erosion mechanism. It was observed that substrate GrA1 steel exhibits lower steady state volume erosion rate in comparison with HVOF sprayed WC-Co/NiCrFeSIB coatings under similar test conditions. It was attributed with higher hardness ratio between silica erodent particle and substrate steel might have caused the penetration of silica particles into the surface which bestow some shielding effect against impacting particles and indentation induced severe plastic deformation.

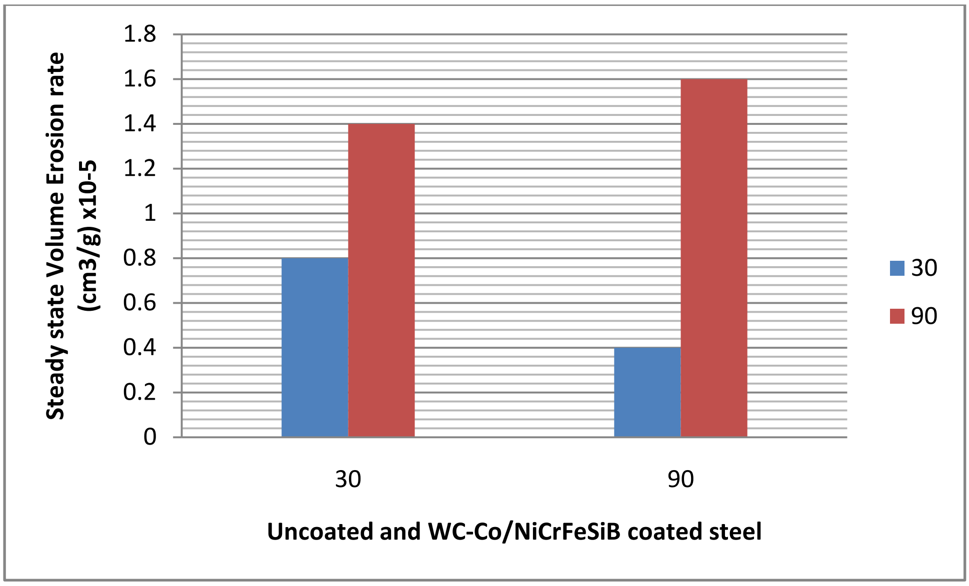

Fig. 17 Histogram illustrating the steady state volume erosion rate of uncoated and WC-Co/NiCrFeSiB coated steel at different impact angles [28]

To investigate the effect of submicron sized WC particles on erosion behaviour of HVOF-sprayed WC-Co coatings **Yuan et al. (29)** incorporated submicron-sized WC particles with the content of 3% wt. and 5% wt. into HVOF sprayed coatings. Microstructure examination by XRD revealed that a small amount of decarburization of the incorporated WC phase takes place after the deposition of composite coating. From SEM microstructure it has been reported that uniform distribution of WC particles takes place at the interfaces of WC-Co splats, which leads to improved wear resistance of the coatings. It has been observed that content of submicron-sized WC particles plays an important role in assessing the wear performances of the coatings. It has been further revealed that with the increment of submicron-sized WC particles, wear rate decreases. It was pointed out that with the increase of WC particle ratio, Vickers micro hardness of the coatings increases. Wear failure analysis of the eroded surface gives further insight into the mechanism of the erosive behaviour enhancement. It was further attributed that the change of stress state and crack initiation at splats interfaces act as the predominant mechanism, which was caused due to the presence of submicron-sized WC particles at splats interfaces.

The Cavitation silt erosion performance of the coating was investigated under different sediment concentration conditions by **Hong et al. [30].** For carrying out the investigation Cr_3C_2–NiCr coating was sprayed on 1Cr18Ni9Ti stainless steel by means of HVOF sprayed process to assess the behaviour of coating under cavitation–silt erosion (CSE) behavior. Different sediment concentration conditions were taken for analyzing the behaviour under cavitation silt erosion. Phase distribution by using XRD images was studied and it was depicted that Cr_3C_2, Cr_7C_3, Cr_2O_3 and (Cr, Ni) phases were present in the coating. It was reported that binder matrix contains amorphous phase and nano crystalline grains. The coating exhibits lower porosity and higher micro hardness. It has been revealed that with the increase in interaction area of sand particles with specimen, the CSE rate has been increased progressively. It further increases with increase in sediment concentration. Micro structural examinations of the eroded surfaces has pointed out that signature of lips, craters, micro cutting, cracks and micro pores contributed for the erosion of the surface of coating. The CSE mechanism for the coating comprises composite behaviour i.e. ductile and brittle mode.

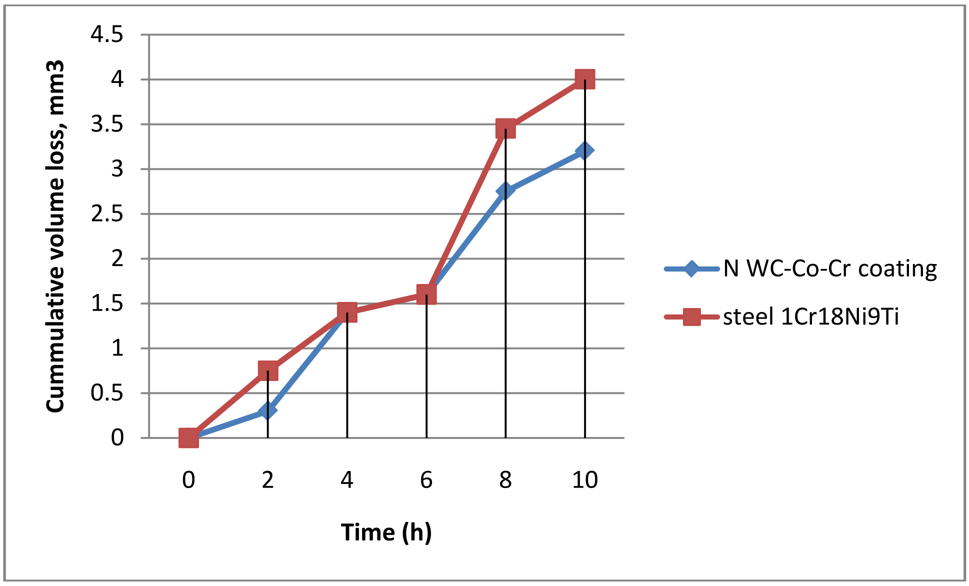

Fig. 18: Cumulative volume loss as a function of time for the coating and the stainless steel 1Cr18Ni9Ti in 3.5 wt.% NaCl solution [30]

To investigate the slurry erosion and corrosion behaviour of HVOF coating **Wang et al.[31]** deposited FeCrMoMnWBCSi amorphous metallic coatings (AMCs)on the 304 stainless steel. Slurry erosion–corrosion testing was conducted by using static electrochemical measurements and weight loss measurements were carried out by rotating the samples under seawater simulated conditions. Fig. XVI shows the variation of E–C rate with sand particle size for 304 stainless steel and AMCs at 18 m $s^{-}1$ in 1 wt.% NaCl containing 12 kg m^{-3} silica sand. It was revealed that Erosion–corrosion rates of the AMCs increased with the increase in flow velocity, particle size content and NaCl concentration. It has been revealed that AMCs are preferentially attacked at coating defects. It has been further revealed that the superior erosion–corrosion resistance exhibited by AMCs might be attributed due to the higher micro hardness, alloying elements and amorphous microstructure. As depicted from the histogram shown in Fig. XVII which reported variation of E–C rate with sand particle size for 304 stainless steel and AMCs, it has been concluded that the AMCs are higher potential coating with better slurry erosion–corrosion resistance which provides the solution to the erosion–corrosion problems which generally occurred in marine pumps under seawater.

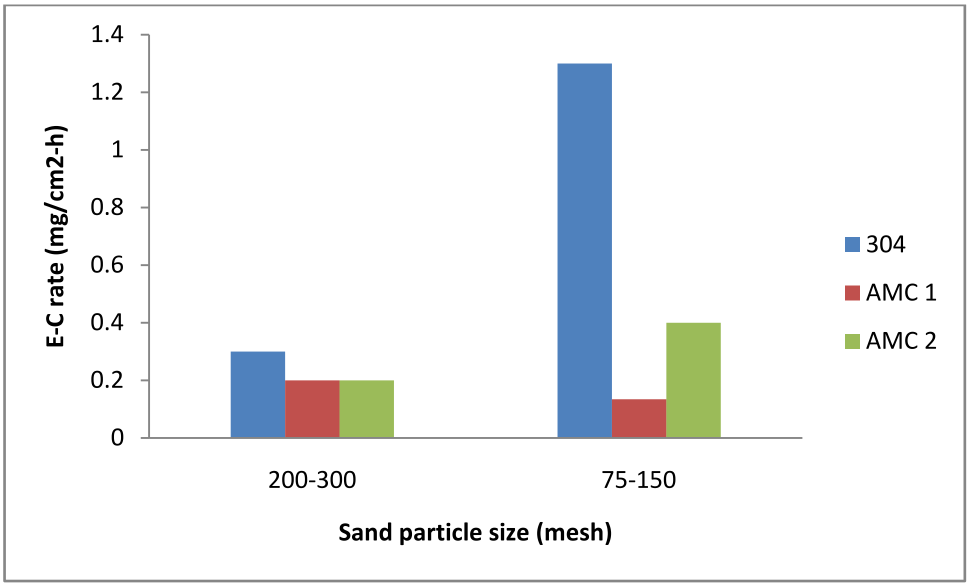

Fig. 19: Variation of E–C rate with sand particle size for 304 stainless steel and AMCs at 18 m $s^{-}1$ in 1 wt.% NaCl containing 12 kg m^{-3} silica sand [31]

To investigate the cavitation erosion resistance of Conventional, submicron and multimodal WC-12Co coatings **Xiong et al. (32)** deposited cermet coating by using HVOF-spray process. The microstructure of the coatings revealed that the coatings prepared by using submicron and multimodal WC-12Co powders by HVOF sprayed are dense, less porous and their micro hardness values are much higher than that of the conventional WC-12Co coating. To analyze the cavitation erosion behaviour, coatings were investigated by using ultrasonic vibration cavitation equipment. Micro structural investigations of the eroded coatings by using SEM pointed out cavitation pits and craters to be the major contributor for cavitation erosion. The average micro hardness of multimodal WC-12Co coating attains HV1500, which is much higher in comparison with that of the conventional and submicron coating. It was further revealed that the multimodal WC-12Co coating depicted as the best cavitation erosion resistant coating among the other three coatings. Erosion rate of WC-12Co coating has been approximately 40% than that of the conventional coating and the cavitation erosion resistances of multimodal WC-12Co coating have been reported to be enhanced by about 150% in comparison with the conventional coating. It was further pointed out that higher erosion resistance was might be due to presence of dense nanostructure, high micro hardness and strong cohesive strength of WC-12Co.

To compare the Conventional weld deposit technique and HVOF-sprayed coating **Mann et al. [33]** investigated the slurry erosion behavior of various coatings such as WC10Co4Cr, Armcore 'M', Stellite 6, stellite 12 HVOF coatings and TiAlN PVD coating on various steels, such as X20Cr13, 17Cr–4Ni pH steel and Ti6Al4V titanium alloy along with conventional hard weld deposits of Stellite 6 and 21. To predict the behaviour under slurry erosion conditions tests were conducted using a water jet impingement erosion apparatus. The slurry erosion investigations were conducted at 60° impingment angle and jet velocity of 18.2m/s alongwith mineral sand of −40 to +80 mesh. Investigation for slurry erosion behaviour testing revealed that WC10Co4Cr HVOF sprayed along with TiAlN PVD coating has been ranked as the best coating materials followed by HVOF coating of Armcore 'M' material. Erosion rate of the various coating is given in the table No IV.

Wu et al. [34] examined the cavitation erosion resistance behaviour of HVOF-sprayed WC–Co–Cr coating onto 1Cr18Ni9Ti stainless steel. By carrying out micro structural examination it was pointed out that there was a presence of amorphous phase, nano crystalline grains (Co–Cr) and several kinds of carbides, including Co_3W_3C, Co_6W_6C, WC, Cr_2C6, and Cr_3C_2 in the coating. Coated substrate has exhibited higher hardness, upto 6 times higher than in comparison with stainless steel substrate. It was also reported from the Fig. XVIII that coated substrate exhibited as higher erosion resistant than the substrate. It was revealed that presence of new phases in the as sprayed coatings, leads to increase in hardness, which further resulted in lesser mass loss which was about 64% than that of stainless steel substrate. During micro structural investigation it was pointed out that maximum mass loss has been taken place in between the interface of unmelted or half-melted particles and the matrix (Co–Cr), edge of the pores in the coatings, boundary of the twin and the grains of the 1Cr18Ni9Ti stainless steel.

Substrate materials and Coating	Volume loss (mm^3)
WC10Co4Cr HVOF coated steel	0.4235
TiAlN PVD coated steel	0.846
Arm core 'M' HVOF coated steel	2.42
Stellite 6 HVOF coated steel	10.3
Stellite 6 weld deposited steel	14.9
Stellite 12 HVOF coated steel	13.55
Stellite 21 weld deposited steel	16.09
X20Cr13 stainless steel	24.48
Ti6Al4V alloy	25.66
Stellite 21 weld deposited steel	16.09

Table 4: Slurry erosion test results of different materials and coating

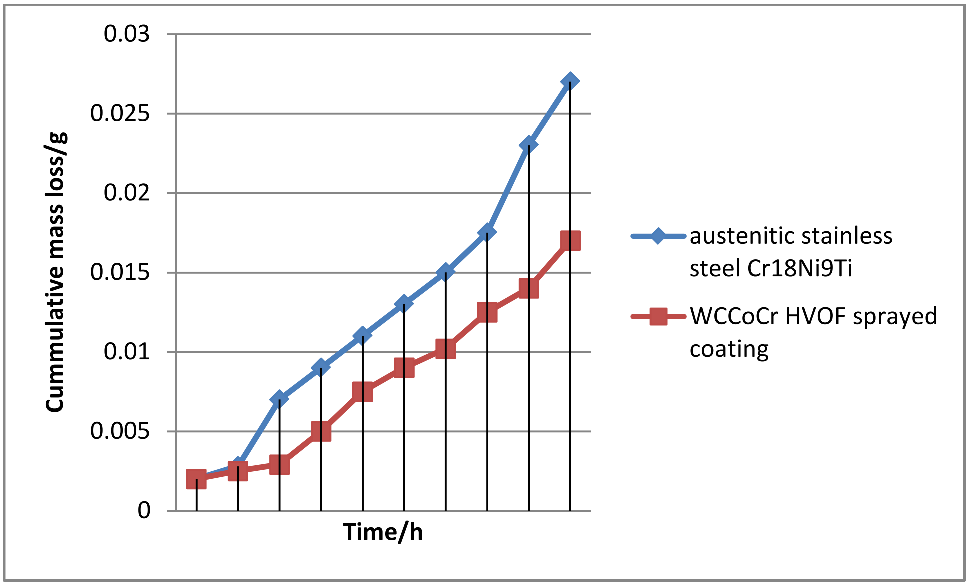

Fig. 18: Cumulative mass losses vs. cavitation erosion time [34]

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To investigate the potential of HVOF-sprayed coating against erosion behaviour **Ramesh et al. [35]** deposited WC-Co/ NiCrFeSiB powder coatings on boiler tube steels. it was found that the coating deposited on base metal exhibited dense laminar structured coating having an average thickness of 290µm and average porosity of 0.5% under the given spray parameters. Due to dense laminar structure of coating, it exhibited higher cohesive strength along with lower porosity of the coating and higher hardness of 1223HV. It was depicted that the erosion resistance of WC-Co/NiCrFeSiB coating was attributed with the availability of ductile and brittle modes of material removal, although brittle mode is dominant. The micro structural analysis of the degraded surface revealed that the formation of craters, groove in binder matrix, lips and platelet and carbide particle pull out were the reasons for existing erosive wear mechanism. Substrate GrA1 steel exhibited lower steady state volume erosion rate in comparison to HVOF sprayed WC-Co/NiCrFeSIB coatings. It was also pointed out that with increase in hardness ratio between erodent particle and substrate steel, higher diffusion of silica particles into the substrate surface takes place which bestows some shielding effect against erodent particles and indentation, it further causes plastic deformation which further resulted in lesser erosion loss.

Conclusion

From the exhaustive study of the work done by the various researchers it has been learnt that the hardness of HVOF coatings plays important role in increasing the wear resistance of the substrate. Researchers found that erosive wear rate depends upon the number of parameters such as velocity, impact angle, concentration and particle size. It has been revealed that for ductile materials and coatings, erosive wear will be significant at lower impact angle (30^o) and for brittle material erosive wear will be maximum at higher impact angle (90^o). In certain cases, material surface does not exhibit sensitiveness with respect to the impact angle and for such material erosive wear was utmost at impact angle of 60^o. Further researchers established a fact that erosive wear rate is directly proportional to the exponent of the kinetic energy imparted by the solid particles. Some of the researchers have been reported that the roughness of the coating plays an important role in wear rate of the coating. It has been assessed that the coatings with higher surface roughness eroded out at faster rate. It has been revealed that among the several HVOF sprayed coating investigated by the researchers, WC coating have exhibited the maximum erosion resistance. Further it has been learnt that HVOF sprayed Stellite coatings have shown higher erosion resistance under water conditions so it can be proposed for utilization under marine applications. From the existing literature on the slurry erosion it can be concluded that HVOF sprayed coating has shown promising result with reference to erosion resistance at various impact angles. From the existing studies in the field of thermal spraying, it was concluded that there is a great scope for utilization of HVOF sprayed coatings under the applications for combating slurry erosion, Wear and corrosion resistance. It has been seen that High velocity oxy fuel sprayed coatings can play important role in protecting materials and alloys from wear, erosion and corrosion phenomenon. Although various coatings such as WC-CoCr, Cr_3C_2-NiCr, Al_2O_3, Stellite, Cr_2O_3, Cr_3C_2–NiCr, NiCrSiB–35wt%WC–Co, WC–10Co–4Cr, nanostructured Ni60–TiB2 and WC-12Co have been investigated by the investigators for providing resistance against wear and slurry erosion, however still need exist to investigate more on HVOF Coating so that composite coatings can be prepared by mixing these powder. Also as we have seen that by using some kind of treatments by the solutions on the substrate and by giving heat treatments to substrate the resistance of HVOF coating improved further. Hence there is great need to work on heat treatment processes and chemical solutions so that resistance of HVOF coating will improved further. Further more extensive research is needed to investigate the effectiveness of HVOF sprayed coatings under real time environment. It was seen that process parameters of HVOF spraying which are used for depositing the coatings have significant effect on the microstructure, mechanical and other properties of the coatings. So there is great necessity to optimize the process parameters of HVOF spraying process. Researchers observed that wear rate depends upon number of parameters such as velocity, impact angle, concentration, particle size. Still there is scope to analyze more about the HVOF coatings.

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