Effects of Tribological Parameters on Slurry Erosion Behaviour of Uncoated and Coated Materials: A Review

Sunil Kumar [1,*], Jasbir Singh Ratol[2]

[1] Chitkara School of Mechanical Engineering, Chitkara University, Rajpura, District Patiala, Punjab, India-140401
[2] Department of Mechanical Engineering, Baba Banda Singh Bahadur Engineering College, Fatehgarh Sahib, Punjab, India-140407

[*]corresponding author: e-mail:sunil14478@yahoo.co.in

Resume

This paper describes the pioneering work of various researchers in the field of slurry erosion behaviour of uncoated and coated materials in various industrial applications. The present study is focused on the slurry erosion behaviour of ash slurry disposal system of thermal power plants. The key components such as impeller and casing of ash slurry disposal pumps in thermal power plants experience this phenomenon of wear. Tribological parameters such as solid particle concentration, impact velocity of erodent on the target surface, impact angle, erodent particle size and shape, hardness of the striking particles and target material, etc. are responsible for slurry erosion. The research results show that the influence of tribological parameters on the slurry erosion is found to be significant and need to be evaluated and analyzed properly. The slurry erosion can be minimized by proper selection of materials and/or by providing the suitable protective coating on the material which can enhance the surface properties.

Available online: http://fstroj.uniza.sk/journal-mi/PDF/2013/16-2013.pdf

Article info

Article history:
Received 17January 2013
Accepted 23April 2013
Online 10 September 2013

Keywords:
Slurry Erosion;
Thermal Spray Coatings;
Physical Vapour Deposition Process;
Chemical Vapour Deposition Process;
Nano-structured Coatings.

ISSN 1335-0803 (print version)
ISSN 1338-6174 (online version)

1. Introduction

Slurry erosion is found to be serious problem in power generation component such as ash slurry disposal pumps (impeller and volute casing) in thermal power plants and hydraulic turbines (runner, guide vanes, needles and seats) in hydro-electric power plants and should be either totally prevented or detected at an early stage to protect the system for maximum utilization. Slurry erosion mechanism is shown in fig. 1. The erodent particles present in the slurry strikes the surface of target material with high velocity and the erosion takes place.

In thermal power plants, the bed ash and fly ash is mixed with clean water in main mixing tank to form combined slurry. Once the combined slurry density reaches the target level, a centrifugal slurry pump conveys the slurry out of the plant [1]. Fig. 2 shows the schematic diagram of ash handling system of thermal power plant. The impeller and volute casing of centrifugal slurry pump get exposed to slurry erosion due to the impact of high velocity ash particles of slurry on the surface of impeller and casing [2].

The target materials may be nickel hardened alloy steels, chromium alloyed cast iron, stainless steel, aluminium alloy, brass, mild steel etc. The solid particles which may use as erodent in industrial applications are fly ash, bed ash, silica sand, quartz, feldspar, muscovite, biotite, garnet, tourmaline, clays, volcanic ash, alumina and silicon carbide etc. Wells et al. [3] have studied the ash content, major minerals and trace elements, in 10 coals and found the maximum ash content in Indian coal. Table 1 shows the Indian coal with dry ash content and mineral matter.

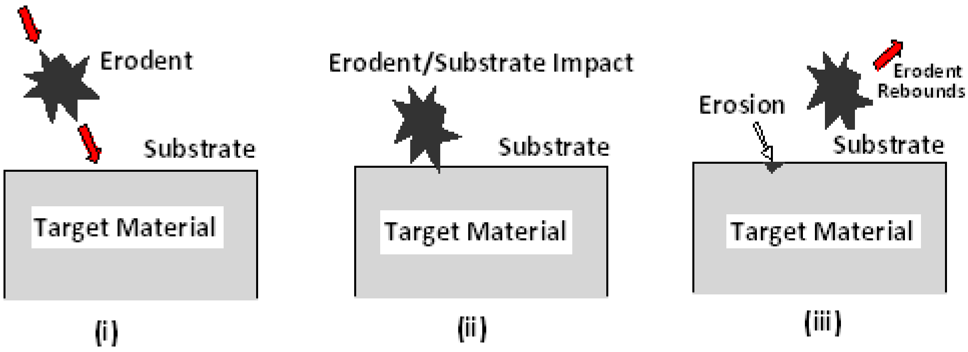

Fig. 1.Slurry erosion mechanism.

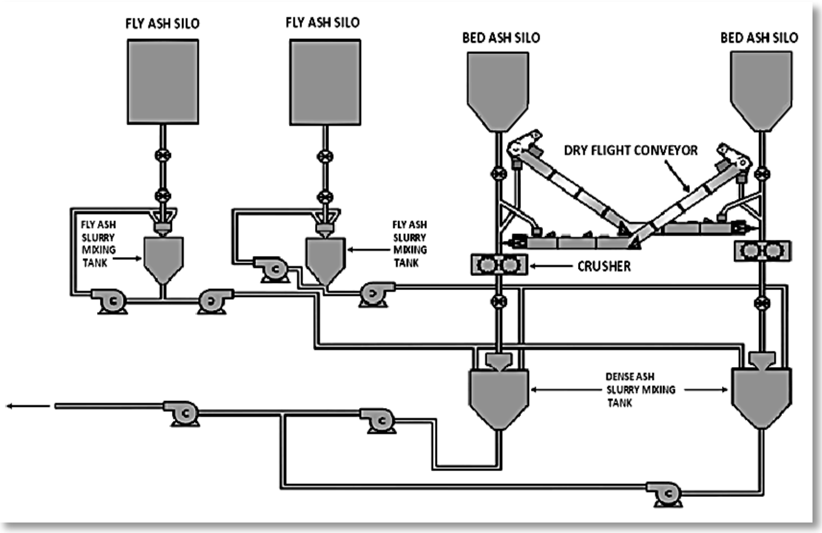

Fig. 2.Schematic diagram of ash handling system of thermal power plant [1].

Table 1

The ash content and mineral matter [3].

Coal	Ash Content (Wt%) dab	Major minerals	Trace minerals
Indian coal A	46.7	Quartz, illitic clay, Kaolinite, muscovite, siderite	Barites, rutile, feldspar, pyrite, ilmenite, zircon
Indian coal B	30.3	Quartz, illitic clay, feldspar, kaolinite, muscovite, siderite	Apatite, garnet, ilmenite, rutile, monazite, zircon
Indian coal C	45.6	Quartz, illitic clay, feldspar, garnet, muscovite, kaolinite	Apatite, rutile, ilmenite, pyrite, monazite, zircon

To dispose huge amount of ash hydraulically from power station to ash pond, the slurry pumps are arranged in series. High wear resistant materials such as nickel hardened alloy steels, chromium alloyed cast iron etc. should be used for ash handling slurry pump components such as impeller and casing. If low strength materials used then properties can be enhanced by applying wear resistant coating on the target surface. Various coating methods are discussed and compared in this paper.

2. Parameters responsible for slurry erosion

The tribological parameters responsible for slurry erosion are solid particle concentration, impact velocity of erodent on the target surface, impact angle, erodent particle size and shape, hardness of the striking particles and target material, physical and chemical properties of the erodent. The data regarding particle size distribution and chemical composition of fly ash is collected from the DBCR Thermal Power Plant, Yamunanagar (India) and shown in table 2 and table 3 respectively. The specific gravity and weighted mean diameter of collected fly ash (unsieved) are 1.992 and 65μm respectively.

Erosion in slurry pumps can be tested by using jet erosion test rig, slurry pot tester, coriolis erosion tester etc. Kumar et al. [2] have conducted experiments on high chrome cast iron as target material and fly ash as erodent and concluded that the erosion on the ash slurry pump impeller and casing primarily depends upon the ash concentration in the slurry followed by the rotational speed of the pump impeller and ash particle size. Erosion of the pump impeller would decreases with decreasing ash concentration, rotation speed and particle size. Clark [4] has investigated the effect of particle velocity and particle size in slurry erosion. A list of factors affecting slurry erosion such as concentration of particles, particle impact speed, particle impact angle, particle size, particle density, hardness, friability, nature of suspending liquid, nature of slurry flow, nature of target material were explained. It is emphasized that material loss must be measured by changes in surface profile rather than mass loss, and that the best specimen form for this analysis is a cylinder.

Desale et al. [5] have conducted experiments on slurry pot tester to visualize the effect of slurry erosion on ductile materials under normal impact condition. It is observed that wear depends upon hardness of target material and hardness of solid particles. The various ductile materials tested were copper, mild steel, brass etc. The erodent materials used were quartz, alumina, and silicon carbide. Experiments were performed at 3m/s velocity and 10 percent by weight concentration of 550 μm size particles for combination of different erodent and target materials at normal impact condition. Desale et al. [6] shows the effect of erodent properties on slurry erosion. Experiments have been performed in a pot tester to evaluate the wear of two ductile materials namely, AA6063 and AISI 304L steel. Solid–liquid mixtures of similar particle sizes of three different natural erodent namely, quartz, alumina and silicon carbide have been used to evaluate the mass loss of the two target materials at different impact angles. The result shows that the maximum angle for erosion is a function of target material properties and does not depend on the erodent. The erosion rate of ductile materials varies with the erodent properties other than its size and hardness. The effect of erodent properties namely, shape and density is more dominant at shallow impact angles compared to higher impact angles.

3. Coatings for wear protection

The coating can be defined as a layer of material, formed naturally or synthetically on the surface of an object made of another material, with the aim of obtaining required properties such as high wear resistance, high corrosion resistance etc [7]. The coating can protect the material from erosion to a great extent. The erosion resistance depends upon the type of coating material used and the coating technique. The coating materials may be metals, alloys, ceramics, cermets, polymers etc. From a production point of view, Sidhu et al. [8]explained three methods to predict coatings, these being thermal spray coating, physical vapour deposition and chemical vapour deposition.

Table 2

Particle size distribution of Fly Ash.

Size (μm)	**300**	**200**	**100**	**75**	**64**	**50**	**41**	**36**	**25**	**17**	**13**	**10**	**4**
% Finer	100	98	90	85	70	64	61	55	43	28	16	8	3

Table 3

Chemical composition of fly ash.

SiO_2	**Al_2O_3**	**Fe_2O_3**	**CaO**	**K_2O**	**TiO_2**	**Na_2O**	**MgO**
54.77%	33.83%	2.79%	0.80%	1.97%	2.76%	0.72%	2.35%

3.1. Thermal spray coatings

Thermal spray coatings are the hard facing techniques available for the application of coating materials used to protect components from erosion, corrosion, abrasive wear and adhesive wear. Generally, any material which does not decompose, vaporize, sublimate, or dissociate on heating, can be thermally sprayed. Consequently a large class of metallic and nonmetallic materials (metals, alloys, ceramics, cermets, and polymers) can be deposited by thermal spray processing techniques. Heath et al.[9] have summarized the thermal spray processes that have been considered to deposit the coatings, are listed below: (1) Flame spraying, (2) Plasma spraying, (3) Electric arc wire spraying, (4) Spray and fuse, (5) High velocity oxy-fuel (HVOF) spraying, (6) Detonation gun spraying.

The thermal spraying techniques have developed at a fast pace due to progress in the advancement of materials and modern coating technology. Plasma-sprayed ceramic coatings are used to protect metallic structural components from erosion and corrosion, and to provide lubrication and thermal insulation [10]. In particular, coatings made of Al_2O_3 containing 13 wt% TiO_2 (Al_2O_3-13TiO_2) are commonly used to improve the erosion resistance of steel. Plasma sprayed zirconia coatings as thermal barrier coatings have been applied to hot section components of gas engines to increase temperature capability of Ni-based super alloys [11]. Mishra et al. [12] have investigated plasma sprayed metallic coating of nickel-aluminide deposited on Fe-based super alloy. The coatings had shown good erosion resistance as compared to the uncoated samples. The properties of plasma and HVOF thermal spray coatings obtained by blending of NiCrBSi and Fe_2O_3 powders have compare and concluded that an optimal content of Fe_2O_3 was 26 % for plasma sprayed coatings and 22.5 % for HVOF coatings [13].

3.2. Physical vapour deposition process

In physical vapor deposition (PVD) process, the coating is deposited in vacuum by condensation from a flux of neutral or ionized atoms of metals [14]. A number of PVD methods are available for deposition of hard coatings. Among them, cathodic arc vapour (plasma or arc ion plating) deposition, magnetron sputtering (or sputter ion plating), and combined magnetron and arc processes are most commonly used methods for the deposition of titanium-aluminium based coatings. The PVD methods are commonly used these days for the improvement of physical and mechanical properties of a wide range of engineering materials. Employing the PVD techniques for coating deposition ensures high erosion resistance. Besides, the ceramic nitrides, carbides present interesting colours which allow them to be used in decorative components (e.g., golden or a polished brass-like) [15]. Rodr´iguez-Baracaldo et al. [16] have studied the high temperature wear resistance of TiAlN PVD coating on untreated and gas nitride AISI H13 steel with different heat treatments. The coated specimens have shown better wear resistance as compared to the uncoated specimens. These coatings exhibit better wear resistance. The erosion performance of M2 tool steel coated with PVD CrN/NbN super lattice coatings, produced by unbalanced magnetron sputtering with bias voltage of -75 V, was assessed and compared to the uncoated tool steel substrate [17]. The results indicated that the performance of the coating depended on the impact angle and the applied potential. The overall erosion resistance of the coated samples was found to be superior to that of the uncoated samples.

3.3. Chemical vapour deposition process

Chemical Vapour Deposition (CVD) process is a versatile process that can be used for the deposition of nearly any metal as well as non metal such as carbon or silicon [18]. The first step is the production of metal vapours. Several chemical reactions can be used: thermal decomposition, pyrolysis, reduction, oxidation, nitridation etc. The main reaction is carried out in a separate reactor. The vapours thus formed are transferred to the coating chamber where the sample is mounted and maintained at high temperature. P´ereza et al. [19] have studied adhesion properties of aluminide coatings deposited via CVD in fluidized bed reactors CVD-FBR on AISI 304 stainless steel. The CVD-FBR technique has been shown to be a very interesting surface modification technology because aluminium diffusion coatings can be produced at lower temperatures and shorter times than by conventional pack cementation. The CVD boron phosphide coatings, which were 20-28μm in thickness, were deposited on AISI type 316 stainless steel substrates and tested under low impact velocity (33 m/s) in an air–sand erosion test rig in order to determine the erosion behaviour [20]. The results indicated that the particle impacts cause the initiation and propagation of radial and lateral cracks, which leads to a gradual removal of the coating. Increasing the coating thickness and/or employing a harder substrate may improve the erosion resistance of the coating.

3.4. Nano-structured coatings

Nano-structured coatings composed of crystalline/amorphous nano-phase mixture have recently attracted increasing interests in fundamental research and industrial applications, because of the possibilities of synthesizing a surface protection layer with unique physical and chemical properties that are often not attained in the bulk materials [21]. Nano-structured materials as a new class of materials with enhanced properties and structural length scale between 1 nm and 100 nm. Nano-structured ceramic coatings produced by Plasma sprayed processes are being developed for such applications that required resistance to erosion, corrosion, cracking and spallation, with improved properties. Singh et al. [22] have investigated and compared the tribological behaviour of the nano-Al_2O_3 coatings on SS-304 substrate with conventional coatings and concluded that the superior erosion resistance of nano-structured coatings as compared to conventional coatings is due to its higher hardness and effective hindrance to crack propagation.

Nano-materials have shown many properties and processing advantages over conventional coarse-grained powders. Shaw et al. [23] have studied the dependency of microstructure and properties of nano-structure and properties of nano-structured coatings on plasma spray conditions. Al_2O_3–13TiO_2 coatings formed via a plasma spray approach using reconstituted nanosized Al_2O_3 and TiO_2 powder. Wear test suggest that the coating produced from nano-powder feedstock could have better wear resistance than the coatings produced using commercial coarse-grained powders. Chuanxian Ding et al. [24] have investigated the plasma sprayed nano-structured zirconia coatings for wear resistance. The plasma sprayed nano-structured zirconia coatings possess a higher wear resistance then their conventional counter parts. The higher wear resistance of the nano-structured coatings is attributed to their optimized microstructure and improved micro-hardness.

Leblanc [25] has evaluated micro-structural, abrasion and sliding wear properties of Atmospheric plasma spraying (APS) and Vacuum plasma spraying (VPS) sprayed Al_2O_3-13TiO_2, Cr_2O_3-5SiO_2-3TiO_2, and TiO_2 coatings from micro-structured and nano-structured powders. Performance of VPS coatings is superior or equal to those of APS coatings. Nano-structured powders are more sensitive to the thermal spray process used, as compared to conventional micro-structured powders. VPS provide a better environment for applying nano-structured oxide ceramic materials, as compared to APS. The superior properties of coatings applied from nano-structured powders seem to be associated with coatings that have retained a nanostructure, i.e. a bimodal structure composed of partially or unmolten particles, combined with fully molten regions. Nano-structured alumina-titania coatings were produced by plasma spray of reconstituted nano-structured powders, using optimized processes, defined by a critical plasma spray parameter [26]. Physical and mechanical properties, including density, hardness, indentation, crack growth resistance, adhesive strength, spallation resistance in bend and cup tests and resistance to abrasive and sliding wear were also examined. The superior properties are associated with coatings that have a retained nano-structure, especially with partial melting of the nano-structured powders.

Jin-hong Kim et al. [27] have developed thermal sprayed nano-structured WC-Co wear resistant coatings and the resultant coatings shown significant improvement of wear resistance in comparison with the conventional counterparts. Micro-structural homogeneity of the conventional Cr_2O_3 based solid-lubricant coatings was obtained by utilizing nano-structured feedstock powder developed. Nano-structured and conventional zirconia coatings were deposited by APS and the thermal shock resistance of coatings was investigated by the water quenching method [28]. The results showed that the nano-structured coatings possessed better thermal shock resistance then the conventional coating. Xinhua Lin et al. [29] have studied the effects of temperature on tribological properties of nano-structured and conventional Al_2O_3-3TiO_2 coatings deposited by APS. The tribological properties of both coatings against silicon nitride ball were examined in the temperature range from room temperature to 600°C. The wear resistance of the nano-structured coating was found better at high temperature as compared to their conventional counterpart.

4. Slurry erosion of uncoated materials

The effect of tribological parameters on the slurry erosion behaviour of uncoated materials (such as nickel based steel alloys, chromium alloyed steels, stainless steels, white iron alloys, aluminium alloys etc.) have been studied by a large number of investigators. Their aim is to suggest the high wear resistant material for the industrial applications. Gandhi et al. [30] have developed a methodology to determine the nominal particle size of multi-sized particulate slurry for estimation of mass loss due to the erosion wear. The effect of presence of finer particles (less than 75μm) in relatively coarse particulate slurry has also been studied. They have observed that addition of particles finer than 75μm in narrow-size or multi-sized slurries reduce the erosion wear. In addition, 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. The reductions in erosion wear due to addition of fine particles decreases with increase in the concentration of coarse size particles. Gupta et al. [31] studied the effect of velocity, concentration, and particle size on erosion. The experiment was performed on slurry 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 particle size.

Tian et al. [32] have observed the erosion of some metallic materials such as high chromium white iron and aluminium alloy using Coriolis wear testing approach. The correlation between wear rate and particle size on the tested materials is developed. Parameters, which should be considered in wear modeling and prediction, have also been addressed. It can be seen that larger solids particles resulted in higher mass loss in all test materials. Although the erosion rates at smaller particle sizes were relatively close within each material group, the wear rate difference was significantly widened with larger particle sizes. The tested high-Chrome white irons showed a wear resistance of 27–140 times higher than that of the aluminium alloys. Both flow rate and solids concentration of slurry affected the wear results of the test materials. The higher the flow rate, the higher the wear rate of test materials. Tian et al. [33] have experimented on Coriolis wear testing. Wear coefficients have been determined for different slurry conditions over a large range of particle sizes. Among the test materials, the harder Cr–Mo white iron alloy demonstrated the best wear resistance under slurry testing conditions. It is also observed that Coriolis wear testing is an excellent approach to simulate the erosion condition within a slurry pump. Beside particle sizes, other particle properties such as particle shape and size distribution also exhibited significant effect on the values of wear coefficients.

Neville et al. [34] have studied the erosion-corrosion behaviour of WC-Metal Matrix composites (EFM, EFW, EGC, and EGG). The materials were eroded by two sizes of silica sand with stream velocities of 10 m/s and 17 m/s at 65 °C. Test was conducted by varying the solid concentration. They evaluated that WC grain size fractions has very little effect on wear. They also concluded that the erosion rate is strongly dependent upon erodent size, impinging velocity and solid loading. Desale et al. [35] have studied the effect of particle size on erosion of aluminium alloy (AA 6063) using slurry pot tester. Quartz particles were used as slurry of eight different sizes varying between 37.5μm and 655μm. Keeping the solid concentration of 20% by weight and velocity as 3 m/s, experiment was conducted. They found that the erosion increases with increase in mean particle size. Nagarajan et al. [36] have studied the effects of ash particle physical properties and transport dynamics on the erosion of three different grades of low alloy steel, using three different power-station ash types. Fly-ash particulate size and concentration, moisture and titania content, impact velocity and angle, duration of impact, and alloy surface roughness were determined to be first-order effects. The results show that the rate of erosion increases with increasing impact velocity of fly-ash on metal and also increases with increasing concentration of fly-ash.

Rajesh et al. [37] have carried out experiments on the effect of impinging velocity on the erosion behaviour of polyamides. The impact angles were 30° and 60° at two impact velocities (80 and 140 m/s). Silica sand is used as an erodent. Surface blackening at the impact zone was observed for all the materials at normal impact and at both the impact velocities. At normal impact and at lower impact velocity (i.e. 80 m/s), a mass gain in the initial period was observed for all the materials except amorphous. The extent of increase in erosion, however, depended on the materials and the angle of impact. The velocity effect was more prominent at the oblique angle of impact. Dasgupta et al. [38] evaluated the effect of sand slurry concentration on steel using DUCOM made TR-41 erosion tester. They also varied the rotational speed and transverse distance during the test. They concluded that increase in the concentration of sand reduces the erosion rate. They also concluded that the erosion rate deteriorates with rotational speed. Walker [39] compared the erosion 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 has shown lower erosion rate than the metal for particle size less than 700μm. Engin et al. [40] have evaluated some existing correlations to predict head degradation of centrifugal slurry pumps. A new correlation has been developed in order to predict head reductions of centrifugal pumps when handling slurries. The proposed correlation takes into account the individual effects of particle. The proposed correlation is therefore recommended for the prediction of performance factors of ‘‘small-sized’’ slurry pumps having impeller diameters lower than 850 mm.

5. Slurry erosion of coated materials

Recent development on coating technology has shown that the hard face coated materials produce better results as compared to uncoated materials. The wide literature is available to visualize the effect of slurry erosion on various coating materials. The proper cleaning of the uncoated material is very important before the application of coating. Hotea et al. [41] have studied the variety of mechanical and chemical cleaning and pre-treatment techniques used prior to coating. The uncoated material may be cleaned by acetone or abrasive shot blast. The thermal spray techniques to deposit coatings consist of atomization and deposition of molten or semi-molten droplets of the coating material on substrates. Bhandari et al. [42] have investigated the slurry erosion performance of detonation gun spray ceramic coatings (Al_2O_3 and Al_2O_3–$13TiO_2$) on CF8M steel. Slurry collected from an actual hydro-electric power plant was used as erodent in a high speed erosion test rig. The effect of concentration, average particle size and rotational speed on the slurry erosion behaviour of these ceramic-coated steels has studied. The analysis shows that the slurry erosion performance of the D-gun spray Al_2O_3–$13TiO_2$ coated steel has been superior to that of Al_2O_3 coated steel. Mann et al. [43] compared erosion of WC-10Co-4Cr, Armcore ‘M’, Stellite 6 and 12 HVOF coatings, TiAlN PVD coatings. Impact angle of 60° and velocity of 20 m/s was kept constant for all experiments. Mineral sand was used as solid particle of slurry. They concluded that WC-10Co-4Cr HVOF coatings show best performance against slurry erosion. WC-10Co-4Cr HVOF coatings have very good erosion resistance but not corrosion resistance. Cheng-Hsun Hsu et al. [44] have investigated the influence of TiN PVD and TiAlN PVD coating on the erosion of austempered ductile iron (ADI) and found that TiN and TiAlN films could be well deposited on the ADI substrate by the PVD method of cathodic arc evaporation. After slurry erosion test, the result revealed that erosion resistance of coated specimens was better than that of uncoated specimens and TiAlN revealed better erosion resistance than TiN due to the effects of hardness.

Bhandari et al. [45] have investigated the slurry erosion performance of detonation gun spray cermet coating (WC-10Co-4Cr) on CF8M steel. Slurry collected from an actual hydro-electric power plant was used as erodent in a high speed erosion test rig. The effect of concentration, average particle size and rotational speed on the slurry erosion behaviour of coated and bare steels has studied. Signatures of microcutting, fracture of well-bonded WC grains and fragmentations were observed on the eroded surface of WC-10Co-4Cr coating, while signatures of formation of plowing, lips, shearing of platelet, formation of crater, and micro-cutting were observed on the eroded surface of CF8M steel. Santa et al. [46] compared the erosion 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 coatings were applied by HVOF. A modified centrifugal pump was used to evaluate the 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 protecting cavitations, in fact shows poorer performance than bare steel. Singh et al. [47] studied that detonation gun spraying is one of the thermal spraying techniques known for providing hard, wear resistant and dense micro structured coatings. Process parameters of detonation spraying influence the microstructure, mechanical and other properties of the coatings. Research is needed in optimization of the process parameters of detonation spraying process. Detonation gun separation device designed by researchers resulted in good performance of the detonation gun spraying in high performance requirement.

Helle et al. [48] investigated that at impingement angle closer to 90°, the ceramic coating do not offer any advantages over uncoated metallic surface, while at an impingement angle closer to zero degree, the ceramic coatings seems to offer wear protection. Harder erodent particles cause more wear on ceramic coatings than do softer particles. Santa et al. [49] studied the slurry erosion of two coatings applied by oxy fuel powder and wire arc spraying processes onto sand-blasted AISI 304 steel and the results were compared to those obtained with AISI 431 and ASTM A743 grade CA6NM stainless steels, which are commonly used for hydraulic turbines and accessories. Slurry erosion tests were carried out in a centrifugal pump, in which the samples were placed conveniently to ensure grazing incidence of the particles. The slurry was composed of distilled water and quartz sand particles with an average diameter between 212 μm and 300 μm and the solids content was 10 wt % in all the tests. The mean impact velocity of the slurry was 5.5 m/s and the erosion resistance was determined from the volume loss results. The coated surfaces showed higher erosion resistance than the uncoated stainless steels.

Kumar et al. [50] have investigated the slurry erosion behaviour of D-gun sprayed Al_2O_3 coated high chrome cast iron by Response surface methodology and the experimentation is done on the high speed slurry erosion test rig. They concluded that Erosion of Al_2O_3 coated high chrome cast iron would decreases with decreasing rotation speed, ash concentration and particle size. The damage of material due to slurry erosion is shown in Fig. 3.

Fig. 3. Alumina coated specimens damaged due to slurry erosion [49]

Mishra et al. [51] studied all the parameters affecting the erosion using jet erosion tester on fly ash-quartz coating. By varying different parameters they evaluate that impact angle is the most significant factor influencing the erosion of fly-ash-quartz coating. They also evaluated that maximum erosion takes place at impact angle of 90°. Mishra et al. [52] studied the erosion wear behaviour of fly ash–illmenite coating using dry silica sand as an erodent. The Taguchi technique was used to investigate the influence of the impact angle, impact velocity, the size of the erodent, and the standoff distance (SOD) on erosion wear. It was found that the impact angle is the most powerful factor influencing the erosion wear rate of the coating. Further, when erosion behaviour of fly ash–illmenite coating was investigated at three impact angles (i.e., at 30°, 60°, 90°), it was revealed that the impact angle is the prime factor and maximum erosion takes place at 90°.

6. Discussion

The materials having high strength such as high chrome cast iron, nickel hardened alloy steels, chromium alloyed steels etc. are used as wear resistant materials in many industrial applications. The erosion resistance of the materials having low strength can also be increased by providing suitable coating material such as zirconia, alumina, chrome carbide, silicon carbide, tungsten carbide, titanium carbide, cermets etc. on the substrate and using a suitable protective coating technique. There is a large scope of investigation of slurry erosion behaviour using CVD and PVD coating techniques because literature available till now is now sufficient to come to any conclusion. Thick coatings can be provided by thermal spray techniques as compared to CVD and PVD coating techniques, therefore used widely to provide erosive wear resistant coatings but they do not protect centrifugal slurry pumps from cavitations

There are advanced coating materials available such as nano-structured materials and cermets whose wear resistance is very high as compared to other materials. The influence of various tribological parameters on the slurry erosion has been observed by many researchers and come to the conclusion that slurry erosion behaviour depends upon the chemical, physical and mechanical properties of the target material and the type of erodent used. The erodent particle velocity in slurry always leads to erosive wear irrespective of other parameters such as solid concentration, erodent particle size, impact angle etc.

The effect of the rotational speed, ash concentration and particle size on the erosive wear for Al_2O_3 coated cast iron was compared with uncoated cast iron and shown in Fig. 4. By comparing the results, it is clear that up to 1400 rpm the effect of erosion is not much but after 1400 rpm there is an exponential growth in wear rate for coated material. Hence the speed must be kept near 1400 rpm for the maximum slurry transport at low wear rate. The graphs for ash concentration vs. wear rate are linear for both metallic and ceramic coated surface but the wear rate is less in the later case due to the high wear resistance of Al_2O_3 coating. It is shown that if the particles are finer than 75 μm, there will be no any significant effect on the wear rate but from 75 μm to 90 μm the increase in wear rate is significant, hence cannot be ignored. When the particle size is very small, it is not having the sufficient internal energy to penetrate or erode the high wear resistant material.

7. Conclusions

- Slurry erosion is observed as serious problem mainly in power generation components and should be either totally prevented or detected at an early stage. All the discussed tribological parameters more or less contribute to slurry erosion. The degradation of the coated or uncoated material due to slurry erosion increases the maintenance cost of the plant.
- The erosive wear resistance of target material having low strength (such as aluminium, brass mild steel etc.) can be increased by providing wear resistant coating on the substrate.
- The development of modern thermal power plants with higher thermal efficiency requires the use of construction materials of higher strength and with improved resistance to the aggressive service atmospheres. These requirements can be fulfilled by protective coatings.

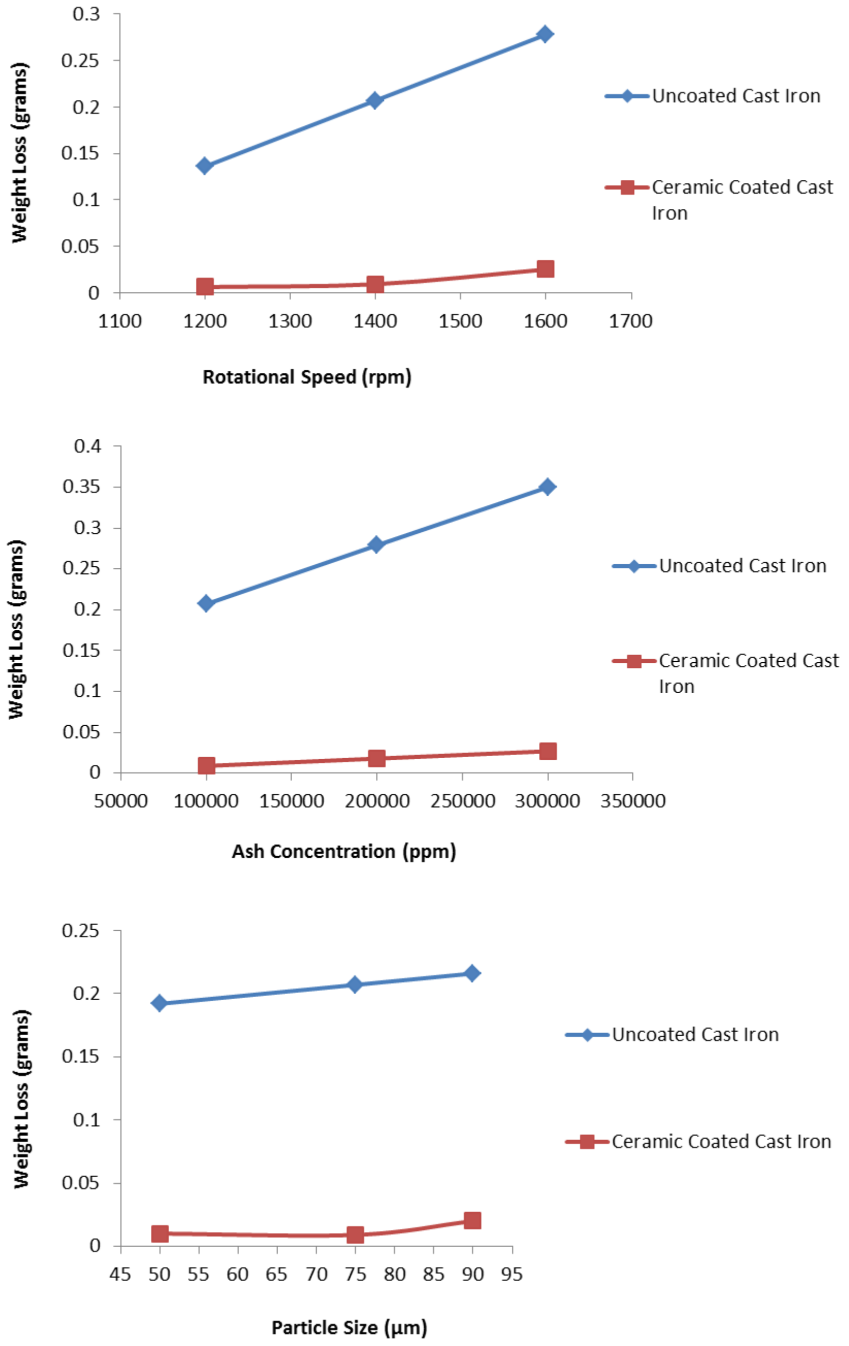

Fig. 4. Comparison of erosion for uncoated and coated samples (weight losses as the function of various parameters).

- Use of suitable uncoated or coated material for a specific application can improve the slurry erosion resistance. The study of physical, chemical and mechanical properties of materials can help for the selection of material.
- At present, many techniques have been identified to minimize the extent of slurry erosion; however considerable research efforts are required to apply and evaluate these techniques.
- The outcome of the study shall be useful to explore the possibilities of use of uncoated and coated materials in actual industrial applications.

References

[1] W. G. Goodrich, D. E. Charhut: Power Generation International, United Conveyor Corporation, Waukegan, Illinois (2003) 1-10N. B. Dahorte, S. Nayak: Surf. Coat. Technol. 194 (2005) 58-67.

[2] S. Kumar, J. S. Ratol: Mater. Eng. - Mater. Inz. 19 (3) (2012) 110-116.

[3] J. J. Wells, F. Wigley, D. J. Foster, W. R. Livingston, W. H. Gibb, J. Williamson: Fuel Process. Technol. 86 (2005) 535-550.

[4] H. M. Clark: Tribol. Int. 35 (2002) 617-624.

[5] G. R. Desale, B. K. Gandhi, S. C. Jain: Wear 264 (2007) 322-330.

[6] G. R. Desale, B. K. Gandhi, S. C. Jain: Wear 261(2006) 914-921.

[7] B. S. Sidhu, S. Prakash: Metall. Mater. Trans. A 37 (6) (2006) 1927-1936.

[8] T. S. Sidhu, R. D. Aggarwal, S. Prakash: Surf. Coat. Technol. 198 (2005) 441-446.

[9] R. Heath, P. Heimgartner, G. Irons, R. Miller, S. Gustafsson: Mater. Sci. Forum 251 (1997) 809-816.

[10] P. Bansal, N. P. Padture, A. Vasiliev: ActaMaterialia 51 (2003) 2959-2670.

[11] B. Liang, C. Ding: Surf. Coat. Technol. 197 (2005) 185-192.

[12] S. B. Mishra, K. Chandra, S. Prakash, B. Venkataraman: Mater. Lett. 59 (2005) 3694-3698.

[13] W. Żórawski, O. Bokůvka: Mater. Eng. - Mater. Inz. 20(1) (2013) 2-11.

[14] S. Paldey, S. C. Deevi: Mater. Sci. Eng. A 342 (2003) 58-79.

[15] L. A. Dobrzanski, K. Lukaszkowicz, A. Zarychta, L. Cunha: J. Mater. Process. Tech. 164-165 (2005) 816-821.

[16] R. Rodriguez-Baracaldo, J. A. Benito, E. S. Puchi-Cabrera, M. H. Staia: Wear 262 (2007) 380-389.

[17] Y. Purandare, M. M. Stack, P. Hovsepian: Wear 259 (1-6) (2005) 256-262.

[18] A. S. Khanna: Introduction to high temperature oxidation and corrosion, ASM International, Materials Park, Ohio, ISBN 0-87170-762-4, (2002).

[19] F. J. P´ereza, U. F. Pedraza, M. P. Hierro, P.Y. Hou: Surf. Coat. Technol. 133-134 (2000) 338-343.

[20] D. W. Wheeler, R. J. K. Wood: Surf. Coat. Technol. 200 (14-15) (2005) 4456-4461.

[21] A. S. Khanna, S. K. Jha, Trans. Indian Inst. Met. 51 (5) (1998) 279-290.

[22] V. P. Singh, A. Sil, R. Jayaganthan: Surf. Eng. 28 (4) (2012) 277-284.

[23] L. L. Shaw, D. Goberman, R. Ren, M. Gell, S. jiang, Y. Wang, T. D. Xiao, P. R. Strutt: Surf. Coat. Technol. 130 (2000) 1-8.

[24] C. Ding, H. Chen, X. Liu, Y. Zeng: In: Thermal Spray 2003: Advancing the science & applying the technology, Eds.: C. Moreau and B. Marple, ASM International, Materials Park, Ohio, 2003, pp. 455-458.

[25] L. Leblanc: Thermal Spray 2003: In: Advancing the science & applying the technology, Eds.: C. Moreau and B. Marple, ASM International, Materials Park, Ohio, 2003, pp. 291-299.

[26] E. H. Jordan, M. Gell, Y. H. Sohn, D. Goberman, L. Shaw, S. Jiang, M. Wang, T. D. Xiao, Y. Wang, P. Strutt: Mater. Sci. Eng. A 301 (2001) 80-89.

[27] Jin-hong Kim, Hyun-seok Yang, Kyeong-ho Baik, ByeungGeunSeong, Chang-hee Lee, Soon Young Hwang: Curr. Appl Phys. 6 (6) (2006) 1002-1006.

[28] B. Liang and C. Ding: Surf. Coat. Technol. 197 (2005) 185-192.

[29] X. Lin, Y. Zeng, C. Ding, P. Zhang: Wear 256 (2004) 1018-1025.

[30] B. K. Gandhi, S. V.Borse: Wear 257 (2004) 73-79.

[31] R. Gupta, S. N. Singh, V. Sehadri: Wear 182 (2) (1995) 169-178.

[32] H. H. Tian, R. A. Graeme: Wear Vol. 258 (2005) 458-469.

[33] H. H. Tian, R. A. Graeme, V. P. Krishnan: Wear 259 (2005) 160-170.

[34] A. Neville, F. Reza, S. Chiovelli, T. Revegav: Wear 259 (1-6) (2005) 181-195.

[35] G. R. Desale, B. K. Gandhi, S. C. Jain: Wear Vol. 266 (11-12) (2009) 1066-1071.

[36] R. Nagarajan, B. Ambedkar, S. Gowrisankar, S. Somasundaram: Wear 267 (2009) 122-128.

[37] J. J. Rajesh, J.Bijwe, B. Venkataraman, U. S. Tewari: Tribol. Int. 37 (2004) 219-226.

[38] R. Dasgupta, B. K. Prasad, A. K. Jha, O. P. Modi, A. H. Yegneswaran: Mater. Trans. JIM 39 (12) (1998) 1185-1190.

[39] C. I. Walker: Wear 250 (1-12) (2001) 81-87.

[40] T. Engin, M. Gur: J. Fluids Eng. 125 (2003) 149-157.

[41] V. Hotea, I. Smical, E. Pop, I. Juhasz, G. Badescu: Annals of the Oradea University, Fascicle of Management and Technological Engineering 7 (17) (2008) 1486-1492.

[42] S. Bhandari, H. Singh, H. K. Kansal, V. Rastogi: Tribol. Lett. 45 (2012) 319-331.

[43] B. S. Mann, V. Arya, A. K. Maiti, M. U. B. Rao, P. Joshi: Wear 260 (1-6) (2006) 75-82.

[44] Cheng-Hsun Hsu, Jung-Kai Lu, Kuie-Liang Lai, Ming-Li Chen: Mater. Trans. JIM 46 (6) (2005) 1417-1424.

[45] S. Bhandari, H. Singh, H. K. Kansal, V. Rastogi: J. Therm. Spray Technol. 21 (2012) 1054-1064.

[46] J. F. Santa, L. A. Espitia, J. A. Blanco, S. A. Romo, A. Toro, Wear 267 (1-4) (2009) 160-167.

[47] L. Singh, V. Chawla, J. S. Grewal: Journal of Mineral & Materials Characterization & Engineering 11 (3) (2012) 243-265.

[48] A. Helle, P. Andersson, T. Ahlroos, V. Kupiainen: VTT Technical Research Centre of Finland, Research Report Number BTUO43-041265, (2004) 15-28.

[49] J. F. Santa, J. C. Baena, A. Toro: Wear 263 (2007) 258-264.

[50] S. Kumar, J. S. Ratol: International Journal of Advances in Engineering & Technology 3 (2) (2012) 403-410.

[51] S. C. Mishra, S. Das, A. Satapathy, P. V. Ananthapadmanabhan, K. P. Sreekumar: Tribol. Trans. 52 (2009) 401-404.

[52] S. C. Mishra, S. Praharaj, A. Satpathy: Journal of Manufacturing Engineering 4 (2) (2009) 241-246.