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A REVIEW OF HVOF COATED STEELS FOR HYDRO TURBINE APPLICATIONS

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Abstract*— In this review, the slurry erosion behaviour of various HVOF coated steels for hydro turbine applications has been addressed. The specific surface characteristics can be imparted to substrate material by selection of suitable coating materials. Hard coating particles such as B_4C and NiCr can be incorporated in structure of composite coatings to obtain refined structure with increased hardness, adhesion and erosion resistance. The various process parameters such as impingement angle, impact velocity and sand discharge have remarkable effect on slurry erosion characteristics of composite coated substrates. HVOF is a promising methodology due to capability of fabrication of hard thermal coatings with high scratch resistance, excellent wear and superior slurry erosion resistance and other advantages associated with the procedure.

Keywords—HVOF, hardness, slurry erosion, scratch resistance, thermal coatings.

I. INTRODUCTION

The major cause of degradation in various parts of hydro turbines like impellers, guide vanes, buckets, nozzles, spears and labyrinth seal is Slurry erosion **[1]**. Sediment erosion process is affected by various factors such as hydraulic design, head, flow rate, turbulence, rotational speed, velocity, acceleration, impingement angle, sediment type and its characteristics, and turbine component material. An integrated approach is needed for predicting the sediment erosion problems **[2]**. A wise strategy need to be developed to study the abrasive and erosive wear in sediment laden water **[3]**. The river sediments (with specific gravity approximately 2.6) are found as silt, clay, sand and gravel. **[4]**. Silting problems can be overtaken by using 3-dimensional approach while dealing with various problems in hydro power plants. Catchment area treatment, effective de-silting arrangements and silt resistant materials are the various techniques to tackle the problems of silting in hydro turbines **[5]**. Silt resistant equipment design can be considered with due attention to Hydraulic design, Mechanical design & Material technology aspects. In Material Technology Approach, The silt erosion can be minimized by developing appropriate turbine materials (metal alloys, ceramics and composites), applying appropriate thermal coating to the turbine material surfaces. i.e. Detonation gun spray, HVOF coating, Vapour deposition techniques, Plasma spray coating etc., and heat treatment processes by which can be very effective in reducing the erosion problems in hydro turbines. In this section our study is limited to turbine materials and coating processes. Various hydro turbine existing materials are 13Cr1Ni stainless steel, 13Cr4Ni stainless steel, 16Cr5Ni stainless steel & 18Cr8Ni stainless steel. Hard thermal coating powders are used to increase the silt erosion resistance thus to increase the life span of base material. Various thermal coating powders include CrC+NiCr, Stellite-6, Cr_3C_2-25NiCr, Chromium Boride, TiB_2 and B_4C **[6]**. Various thermal coating techniques has been developed in recent years like Detonation Gun Spraying Process, Plasma Spraying, Vacuum Plasma Spraying, Wire Arc Spray and High Velocity Oxygen Fuel Spraying (HVOF). HVOF process is extensively used due to excellent adhesion strength, hardness and wears resistance. In this process, a mixture of fuel (gaseous or liquid) and oxygen is ignited in a combustion chamber resulting in production of hot gas (at 1MPa pressure) which passes through a converging–diverging nozzle and a straight section. Generally used gaseous fuels are hydrogen, methane, propane, propylene, acetylene, natural gas etc., and or liquids like kerosene, etc.. The jet velocity in the range of 900-1000 m/s is used. Gas stream accelerates the powder up to 800 m/s. The powder along with hot gas stream is directed towards the substrate surface. Coating with low porosity and high bond strength is deposited upon the substrate **[7].** In this paper, a review of HVOF coated steels for hydro turbine applications has been represented.

II. LITERATURE REVIEW

Mann and Arya [8] investigated the erosive and abrasive wear characteristics of HVOF and plasma nitriding (WC) coatings on13Cr-4Ni and 12Cr steel which are commonly used in hydraulic turbine blades. Hydrofoils were scaled down to 1/10 of actual turbine. A better performance of HVOF coated steel than plasma nitrided 12Cr and 13Cr–4Ni steels were observed. Microstructures of HVOF sprayed WC show few voids (defect) which can cause deterioration at higher temperature range. Plasma nitrided 12Cr and 13Cr–4Ni steels do exhibit these defects but they lack abrasive resistance and erosive wear resistance due to their low micro-hardness values as compared to erodent. Under similar conditions plasma nitrided 12Cr steel performed much better as compared to plasma nitride13Cr–4Ni steel. This is mainly attributed higher micro hardness of 12Cr and its ability to absorb more nitrogen.

Mann [9] investigated the erosion resistance of hard coatings such as plasma nitriding, hard chrome plating, boronising and D-gun spraying of WC on 13Cr-4Ni and T410 steels under liquid-solid impingement. Mineral sand having mean diameter of 135µm was used as the erodent. Under identical conditions, the borided T410 steel was found to be free from cracks and voids, showed much better performance than D-gun sprayed WC as well chromium carbide, plasma nitriding, hard chrome and boronised 13Cr–4Ni steel. D-gun sprayed chromium carbide and WC show a few voids and oxide defects on the surface and at high impact Velocities, these defects could lead to deterioration of the coating surface. The borided 13Cr–4Ni steel also has some cracks and these cracks extend from top of the surface to bottom of the coating. Microstructures of plasma nitrided and hard chrome samples did not show these defects. However, they lack the abrasive wear resistance due to their low value of micro-hardness as compared to that of erodent.

Bashal et al. [10] investigated the slurry erosion behaviour of laser treated 16Cr-5Ni stainless steel under liquid-solid jet impingement. A coating of walex-50 with polyvinyl acetate was deposited on 16Cr-5Ni specimen then treated it with fiber coupled diode laser. It was found that laser-modified hardened sample had higher micro-hardness compared to as-received 16Cr–5Ni specimen. Mass loss tests were carried out at different slurry velocities, 10 and 12 m/s, and at three different angle of impact, 30°, 60° and 90°. For laser-treated 16Cr-5Ni, the volume loss was reduced by ~3.03-fold at 10 m/s, and 2 fold at 12 m/s as compared to the as received sample. At impact velocity of 12m/s, the erosion mechanism for substrate was of mixed (ductile and brittle) type, while at 10m/s, the erosion mechanism was of ductile type only. The erosion mechanism for laser treated 16Cr-5Ni at impact velocities of 10 m/s and 12m/s was of mixed type and of ductile type respectively. The erosion resistance of laser treated, Wallex-50 coated 16Cr-5Ni is twice as compared to as received 16Cr-5Ni steel.

Kumar et al. [11] studied the slurry erosion behaviour of HVOF (Cr_2O_3 and CrC + NiCr) coating on 16Cr-5Ni steel under different slurry velocities i,e. 35m/s, 50m/s, 60 and 70m/s at normal angle. Slurry erosion test, XRD phase analysis, porosity measurement by image analyser, surface roughness test by centre line average method, SEM and stereoscopic microstructure analysis tests were performed. Experiment showed that erosion rate is maximum at impact velocity of 50 m/s. Cr_2O_3 coatings exhibit better hardness, low porosity and wear resistance as compared to that of CrC-NiCr coatings. Wear resistance of 16Cr-5Ni steel has improved by both the coatings.

Chauhan et al. [12] developed a nitronic steel (21-4-N) alloy to overcome the maintenance problems that occurred in 13Cr-4Ni steel in hydraulic turbines and compare the erosion behaviour of both these alloys under air-particle impact test. Toughness (Charpy) test, Vickers microhardness test, SEM microstructure analysis tests were performed. It was observed that the 21–4–N nitronic steel is having better erosion resistance as comparison to 13Cr-4Ni martensitic stainless steel, which is mainly attributed to the distribution of hard carbides in the stabilised austenite matrix. Simultaneously austenitic matrix of the nitronic steel have high tensile toughness, high hardness and high strain hardening rate in comparison to 13Cr-4Ni stainless steel, which leads to their higher erosion resistance.

Shivamurthy et al. [13] investigated the slurry erosion behaviour of commercial Colmonoy 88 and Stellite 6 powders coatings deposited on 13Cr-4Ni steel by two stage laser surface alloying process. White silica sand having average size of 100µm was used as the erodent in the experiment. Size distribution test of pure silica sand by tri laser technology, composition analysis by EDAX, SEM microstructure analysis, XRD phase analysis and Vickers micro hardness tests were performed. Experiment showed that surface hardness of Colmonoy 88 and satellite 6 coatings increases 1.25- 2 times as compared to as received 13Cr-4Ni substrate which is mainly attributed to the formation and uniform distribution of complex carbides and borides in Colmonoy 88 and Stellite 6 coatings. The erosive wear rates of both LSA coatings were found to be increase linearly with slurry impingement angle. Both Colmonoy 88 and Stellite 6 coatings show a brittle characteristics of material removal, while 13Cr-4Ni steel substrate shows mixed mode of erosion behaviour. The erosion rate for colmonoy 88 deposits was found to be almost 40% lesser than 13Cr–4Ni steel for all tested conditions.

Grewal et al. [14] investigated the effect of various process parameters i.e. velocity, impingement angle, particle size concentration, and shape on slurry erosion behaviour of CA6NM (13Cr-4Ni) steel under solid-liquid impingement. Erosion rate test, XRD phase analysis, SEM surface microstructure analysis, regression- based model analysis and Vickers micro-hardness tests were performed. At normal angles, the erosion is influenced by platelet formation at the centre of impact zone, while ploughing and micro-cutting were observed for erosion of the material, whereas at 30° angle ploughing along with proposed mixed cutting was observed to be the dominant mechanism for material removal. However, material removal in the form of fragments through plastic indentation mechanism was also seen at high velocities. Erosion mechanism was also found to change with radial distance from the impact zone.

Manisekaran et al. [15] investigated the slurry erosion behaviour of 13Cr-4Ni which is hardened by both laser hardening and pulsed plasma nitriding separately under liquid-solid impingement. Effect of impingement angle and particle size has been discussed. Silica sand having size 150-300µm was used as the erodent. Microstructure analysis by optical microscope and SEM, mass loss test, XRD phase analysis and Vickers micro-hardness tests were performed. Due to the martensitic transformation of retained austenite, laser hardening process has shown better performance at all tested angles as compared to pulsed plasma nitriding process. According to SEM analysis, plastic deformation mode was the dominant material removal mechanism in laser hardened steels while chip formation and micro-cutting was dominant material removal mechanism in the steels treated with pulsed plasma nitriding. Erosion with particle size 150-300 µm size was found to be twice when compared to the particulates having size less than 150µm.

Santa et al. [16] investigated the effect of thermal spray coatings on slurry behaviour of AISI 304 steel and the results were compared to those obtained with CA6NM and AISI 431 steels. E-C 29123 powder was coated by Oxy-fuel powder deposition method and T35MXC powder was coated by wire arc spraying to AISI304 separately. Quartz sand having average particle size 212-300µm was used as the erodent. SEM- EDS microstructure analysis, porosity test by digital image analyser, slurry erosion rate test, Vickers micro hardness tests were performed. It was found that coated stainless steel surfaces have higher erosion resistance as compared to uncoated surfaces, moreover, E-C 29123 coatings deposited by OFP process on the steel substrate showed best erosion resistance and lower material loss of the studied materials. SEM observation showed the plastic deformation in coated and bare stainless steels, and some brittle fractures in the micro-structure.

Singh and Bhandari [17] investigated the slurry erosion behaviour of detonation gun (D-gun) sprayed ceramic coatings (Stellite-6 and Cr_3C_2-25Ni_4Cr) on 13Cr_4Ni steel under liquid-solid impingement. Silica sand having average diameter of 600µm was used as the erodent in this experiment. Mass loss test and SEM-EDS microstructure analysis were conducted. It has been observed that at impingement angle of 30°, the Stellite-6 coating has better slurry erosion resistance than Cr_3C_2-25Ni_4Cr coating and uncoated steel, while for normal impingement angles, uncoated 13Cr4Ni showed better erosion resistance followed by Cr_3C_2-25Ni_4Cr coatings. At normal impingement angles, fatigue and brittle damage was found to be the dominant material removal mechanism, while at an impingement angle of 30°, ploughing with fatigue failure was the dominant material removal mechanism for the materials tested.

Mann et al. [18] investigated the effect high power diode laser surface treatment of Ti6Al4V, 17Cr-4Ni, X20Cr13 PH and X10CrNiMoV1222 steel on their liquid droplet erosion resistance and compared the results with each other. It was found that high power diode laser treated X20Cr13 steel has better erosion resistance performance followed by X10CrNiMoV1222 steels among all the materials tested in the experiment. After HPDL treatment of Ti6Al4V, the erosion resistance was increased substantially, although, the increase in micro hardness was marginal. The grain size of the laser treated materials was much smaller as compared to untreated substrates and after long period of exposure, deep micro tunnels showing micro jetting effects are observed, which is similar to cavitation erosion mechanism. The HPDL treated X20Cr13 steel was found to have three time better erosion resistance than conventionally hardened steel.

Bhandari et al. [19] studied the effect of concentration, average size of the particles and rotational speed on the slurry erosion behaviour of detonation gun sprayed ceramic coatings (Al_2O_3 and Al_2O_3-13TiO_2) on CF8M steel under liquid-solid impingement. Silica sand having average particle size of 100µm and 300µm was used as the erodent. The slurry erosion resistance of D-gun sprayed Al_2O_3–13TiO_2 coated steel was much better as compared to that of Al_2O_3-coated steel which is attributed to the higher toughness of Al2O3-13TiO_2 coatings. For Al_2O_3-13TiO_2 coatings, material removal mechanism was governed by fatigue and brittle fracture, whereas brittle fracture was dominating material removal mechanism in Al_2O_3 coatings. For Al_2O_3 coated substrates, average particle size and slurry concentration were observed to be more dominant factors, while for Al_2O_3- 13TiO_2 coated substrate, rotational speed was more dominant.

Shivamurthy et al. [20] investigated the slurry erosion behaviour of commercial Co- based Stellite 6 and Ni-based Colmonoy 88 powders coatings deposited by laser surface alloying on the surface of 13Cr-4Ni steel under liquid-solid impingement. Silica sand having average particle size 100 and 375µm was used as the erodent. Erosion resistance of laser surface alloyed coatings was found to be increase by 2 to 3 times with impingement angle when compared to the substrate. The hardness of satellite 6 and colmonoy 88 coatings increased by 1.5 and 2 times respectively, after laser surface alloying as compared to the substrate. Stellite 6 coatings showed a mixed (ductile and brittle) mode of erosion behaviour mechanism, while a brittle mode of erosion behaviour mechanism was observed for Colmonoy 88 coatings, when both these coatings were impacted with particles having an average size of 375µm. However, only brittle mode of erosion was dominant mechanism for both LSA coatings when they were impacted with particles having an average size of 100µm.

Bhandari S. et al. [21] investigated the slurry erosion behaviour of Detonation gun sprayed WC-10Co-4Cr Coatings on CF8M steel under liquid-solid impingement. Sand collected from the river having average particle size of 100 and 300µm was used as the erodent. Taguchi method was applied to study the effect of various parameters on erosion characteristics. It was found that erosion resistance of CF8M steel has increased after D-gun spraying of WC-10Co-4Cr coating on it. For CF8M steel under slurry impingement, slurry concentration and rotational speed were the dominant factors for the erosion characteristics, while for D-gun-sprayed WC-10Co-4Cr coatings, average particle size was found to be more dominant factor in comparison to rotational speed and slurry concentration. Experiment also showed that abrasive processes (cutting/ploughing) are mainly responsible for wear losses in CF8M steel at shallow impact angles, whereas wear losses in case of WC-10Co-4Cr coatings occurred due to brittle fracture, at large impact angles (close to 90°).

Zheng et al. [22] studied the transition behaviour of 304 stainless steel and Fe based amorphous coating (Fe54.2Cr18.3Mo13.7Mn2.0W6.0B3.3C1.1Si1.4) from passivation to erosion-corrosion at critical flow velocity of sand - NaCl solution. Potentiostatic test, open-circuit potential monitoring and mass loss tests were conducted to calculate the critical flow velocities. CFV's calculated by using three different methods were in well agreement with one another. It was found that velocities below CFV did not show any impact on passive material and both material loss & surface roughness increases for flow velocities greater than CFV.

Sasaki et al. [23] investigated the erosion-corrosion behaviour of stainless steel (304L) under the impact of 0.6M NaCl solution jet without entrained solid particles. Phase analysis was done by XRD and open-circuit-potential was monitored in an electrochemical cell. It was found that open-circuit potential of 304L stainless steel in 0.6 M NaCl solution increase with time until it attains the pitting potential.

Zhang et al. [24] investigated the erosion-corrosion behaviour of Al3003 alloy in ethylene glycol-water solution by mass loss and electrochemical measurements as well as surface characterization (SEM) through an impingement jet system. Al alloy E–C is dominated by erosion components, i.e., pure erosion and corrosion enhanced erosion, which account for 92–97% of the total E–C rate under the various conditions in this work. Contribution from corrosion components, including pure corrosion and erosion-enhanced corrosion, is slight. With the increase of fluid flow velocity and sand concentration, the total E–C rate increases. Compared with the significant increase of the rates of erosion components, the increase of the rate of corrosion component is negligible. Under normal impact, the surface film would be broken and damaged, but still stay on the electrode surface to provide somewhat protectiveness. With the decrease of impact angle, shear stress becomes dominant and would thinner and completely remove the film, resulting in an increasing E–C rate.

Mohammadi et al. [25] investigated the effect of cold work on erosion-corrosion properties of stainless steel (304L) through a slurry and single particle impact test using silica sand-water slurry. Hardening process is done by TA-215 stanat rolling machine. X-rat mapping of surface, Vickers hardness test, weight loss measurements, specific energy measurements and potentiostatic tests were performed. Specific energies were found to be constant for cold worked samples at various impact velocities. The coefficient of friction between the particle and the surface was independent of amount of cold work.

III. **CONCLUSIONS**

- Silt erosion problem is a serious problem which can be minimised by suitable techniques but cannot be completely eliminated. There is a huge scope of research in the field of turbine erosion.
- The erosion intensity depends on hydraulic design, characteristics of sediments, and process parameters (flow rate, head, rotational speed, velocity, acceleration, turbulence, impingement angle etc.), and turbine components material.
- Silt erosion can be minimized by a good hydraulic and mechanical design but this task is not so easy and is time consuming and costly. Thermal spray coatings can be a good alternate to tackle the silt erosion problems.
- The various turbine blade materials are 13Cr-1Ni, 13Cr-4Ni, 16Cr-5Ni, 7Cr- 4Ni, 18Cr-8Ni stainless steels, 21-4-N Nitronic steel, AISI304 steel, Ti6Al4V etc. Out of which 13Cr-4Ni and 16Cr-5Ni stainless steels are having good erosive and corrosive characteristics.
- Various thermal spray coating techniques has been developed e.g. D-gun spray, HVOF coating, Wire arc spray coating, Vacuum plasma spray, Physical vapour deposition, Chemical vapour deposition, Cold spraying, warm spraying, etc.
- Various coating powders has been developed for hydro turbine blade e.g. Walex-50, Cr_2O_3, CrC+NiCr, Stellite-6, colmonoy 88, E-C 21123, T35MXC, Cr_3C_2-25NiCr, Al_2O_3, Al2O3-13TiO_2, etc.
- Some heat treatment processes has also been applied to enhance the surface hardness of the turbine materials i.e. Plasma nitriding, chrome plating, boronising, laser treatment, pulsed plasma hardening, etc.
- Carbide coatings has shown good wear resistances but very limited research has been done till now in this category of materials. Boron treated steel has good wear and corrosion resistance but very few research has been done which include boron or its compounds for hydro turbine blade coatings.

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