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Slurry erosion of thermal spray coatings: Effect of sand concentration

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Abstract

Slurry erosion is a major problem in hydroturbines and other fluid machineries wherein erodent particles entrained in carrier fluid impinge upon the target surface to cause its degradation. Several possible alternative solutions are available to control slurry erosion; however, surface coatings developed using thermal spraying are mostly used owing to their versatile nature. In this work, Ni based thermal spray coatings were deposited on a commonly used hydroturbine steel (CA6NM), with Al₂O₃ mixed in different proportions. Coatings were developed using high velocity flame spray process (HVFS). Slurry erosion performance of prepared coated and bare steel was investigated using a specially designed jet type test rig with sand as erodent particles. To investigate the effect of concentration on erosion behavior, sand was mixed in water at two different levels, 0.1 wt % and 0.5 wt %. It was observed that all the coatings helped in improving the erosion resistance of the steel with one containing 40 wt % Al₂O₃ showing the maximum improvement. This was related to the microstructure, which controlled the micro hardness and fracture toughness of the coatings. Shielding effect of the rebounding particles was found to have profound effect as erosion rates did not show similar augmentation with concentration. Fracturing of alumina phase along with removal of coating in form of splats was observed to be prominent erosion mechanism.

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Nomenclature

C concentration of sand particles (wt. %)

E erosion rate (mm³/min)

K constant

Superscripts

n exponent of concentration

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1. Introduction

The presence of sand particles in the river water fed to hydroturbines results in their severe degradation. The impingement of the sand particles entrained in water on to the solid surface results in the removal of materials, known as slurry erosion. Erosion of hydropower plants may result in substantial loss of revenues. According to an estimate given by Mann and Arya [1], in 1998, India incurred a loss of US \$ 120 – 150 million due to slurry erosion. Another government report says that shutting down of Naptha Jhakri power plant during the periods of high silt load, resulted in a loss of US \$ 77 million during the year 2003 to 2005 [2].

To reduce the damaging effects of slurry erosion, various surface modification techniques are utilized. These techniques provide low cost solution to deal with such degradation. Among these techniques, thermal spraying has attracted considerable attention worldwide owing to its versatile nature. It has been observed that among different coating compositions investigated in the literature, WC based coatings have been widely investigated. However, the coating compositions comprised of Ni-Al₂O₃ have not been given due attention [3]. Moreover, no attempt has been made in the past to investigate the role of alumina content on the erosion performance of thermal spray coatings. Some recent attempts have been made by the authors wherein, effect of impingement angle and impingement velocity were studied. However, effect of erodent concentration has not been investigated for this coating composition.

The effect of concentration has been investigated earlier by many investigators for different coating systems [4-8] and it was concluded that correlation between erosion rates and concentration is highly nonlinear in nature. Initially, erosion rates increase with corresponding rise in concentration level, however, beyond a critical value, the interference between the rebounding and incoming particles starts to play an important role. Turenne et al [9] showed that erosion rates follows a power law dependency upon concentration. Stack et al [6] investigated the synergism among the erosion and corrosion at different velocity, concentration and potential levels on WC/Co-Cr coating and bare mild steel. Prasad et al [5] also showed that erosion rates had highly non-linear interaction with the concentration. They also observed that highest erosion rates were observed at an intermediate level of concentration. Some of the investigators have observed the adverse effect of concentration on erosion rate. In the present work, effect of erodent concentration on erosion response of Ni-Al₂O₃ based coatings was investigated. Further, possible erosion mechanism is also investigated.

2. Experimentation

2.1. Materials

A hydroturbine steel, CA6NM (ASTM 743) was used as a substrate material for the deposition of the coatings. Coating compositions includes Ni and Al₂O₃ mixed in different proportions. The scanning electron microscope (SEM) (JEOL, JSM 6610LV) micrographs of the feedstock powders are shown in Fig 1. It can be observed that Ni particles, in general, exhibit a round regular morphology, whereas, alumina particles seem to be formed from agglomeration of smaller particles and have blocky appearance [3]. A High Velocity Flame Spray (HVFS) system, is a proprietary product of Metallizing Equipments Company Pvt. Ltd. (MECPL) Jodhpur, India. HVFS system was used for the deposition of the coatings; Table 1 shows the designation system adopted for the developed coatings. For cross-sectional examination, the coated samples were sectioned using a slow speed diamond saw and mounted in epoxy. The mounted samples were grounded using emery papers down to 1500 grit, followed by cloth-wheel polishing using slurry of 1 µm alumina powder. The coatings were characterized using SEM, equipped with energy dispersive spectroscopy (EDS) [Oxford 51-ADD0013] and X-ray diffraction (XRD) [PANalytical X'pert Pro] analysis. Residual stresses in the coatings were also measured using XRD technique. The indentation technique was used for the determination of microhardness and fracture toughness of the coatings using a microhardness tester (Wilson MV 402D). The reported values of the microhardness and fracture toughness are the average of 20 readings obtained from the indents, made at random locations for each sample.

Sand used for slurry erosion testing was collected from river Sutlej (Punjab, India). The collected sand was sieved using sieve shaker machine and all the sand particle having size > 300 µm were discarded. This was done to ensure that test conditions are identical to actual ones. The size of the sand that passes through hydroturbines is

usually smaller than 300 μm . The average microhardness of sand particles was 1600 HV with standard deviation of 200 HV. The XRD analysis of the sand indicates SiO_2 as the primary constituent. In addition to SiO_2 , the presence of Al_2O_3 and Fe_2O_3 can also be observed.

Table 1. Nomenclature used for designating the coatings

Composition	Ni+20 wt. % Al_2O_3	Ni+40 wt. % Al_2O_3	Ni+60 wt. % Al_2O_3
Designation	Ni20A	Ni40A	Ni60A

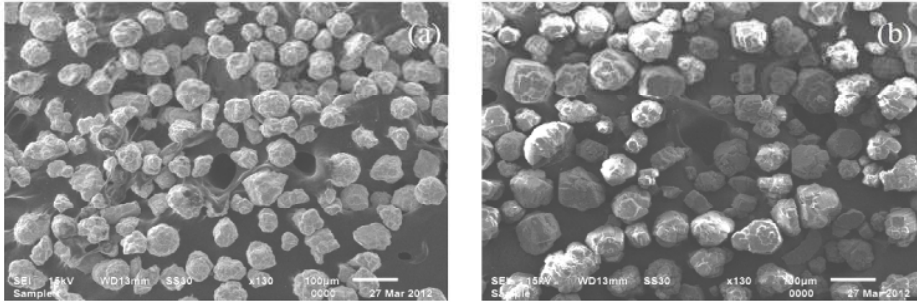


Fig. 1. SEM micrograph of (a) Nickel powder and (b) Alumina powder used for coating

2.2. Test rig and procedure

Slurry erosion tests were carried out in specially designed rig. This rig facilitates testing at different sets of parameters. It has built-in flexibility which allows impact velocity (v), angle of impingement (θ), mass flux rate (m), particle size (S) and distribution (d), and stand-off distance between nozzle outlet and target surface to be controlled easily. Specific details of this rig can be found in Grewal et al [10]. The nozzle of the rig consists of tungsten carbide insert to reduce the degradation of the nozzle. This could help in minimizing the variation in velocity due to change in nozzle shape and size.

Slurry erosion testing was conducted in accordance with the procedure given in ASTM standard G-73. Erosion tests were performed on the coatings prepared with varying proportion of Al_2O_3 . For comparison, erosion performance of uncoated CA6NM steel samples was also studied. Prior to testing, all the samples, coated as well as uncoated, were prepared using the technique discussed in previous sub-section. Mass loss measurements were performed using a precision weighing balance of an accuracy of 0.01 mg. Samples were washed with acetone and dried in air before weight measurements. Slurry erosion tests were performed at a set value of stand-off distance of 20 mm. Prior study [11] showed that maximum erosion of coatings takes place at 90° impingement angle. Therefore, a fixed impingement angle of 90° was used in the present investigation. Velocity of the sand particles, which in the present investigation was considered equal to that of the carrier fluid (water) was maintained at 4 ± 0.5 m/s. To ensure repeatability and accuracy during experimentation velocity was continuously monitored using ultrasonic type flow meter. Effect of sand particles concentration in water was investigated at two levels viz. 0.1 and 0.5 wt. %. The upper level of concentration was selected to replicate the actual working conditions in hydropower plants. Hydropower plants are normally shut down when concentration of sand particles exceeds 0.5 wt. % of water. Further, significant difference among the levels of the concentration would help in understanding the effect of impact frequency on erosion performance of the coatings. At 0.1 wt. %, the frequency of particles striking the target surface is around 382 particles/ mm^2 s, whereas, at 0.5 wt. % the frequency of impacts could be around 1911 particles/ mm^2 s. These two cases can represent high and low cycle fatigue conditions. Testing was conducted for a total exposure period of 10 mins with weight measurements taken after interval of 1 minute. The eroded surface of

the coatings and bare steel was analyzed using SEM after every 1-minute cycle. This was done so as identify the change in erosion mechanism with time, if any.

3. Results and Discussion

3.1. Characterization of coating

The surface morphology of the as-sprayed Ni-Al₂O₃ coatings is shown in Fig 2. The coatings have a typical splat-like microstructure. The alumina splats exhibit pan-cake like structure, whereas, splats of Ni represent a flower like morphology. The arrowheads in Fig 2 indicate the pores and other coating defects such as un-melted or partially melted particles. The detailed microstructural and mechanical characterization of the coatings can be found in Grewal et al [3]. Various mechanical and microstructural properties of coatings are reproduced in Table 2. It can be observed that the presence of alumina has a strong influence on these properties. Presence of 20 wt % Al₂O₃ caused the hardness of the coating to increase by two folds in comparison to the base steel. Further addition of Al₂O₃ content showed a proportional improvement in hardness. The fracture toughness, however, showed a non-linear trend. It was observed that the propagation of cracks was effected by the microstructure of the coating. Porosity and surface roughness were found to increase proportionally with Al₂O₃, which could be related to the coating composition and microstructure [3]. The compressive residual stresses also exhibited linear trend with maximum stresses observed for the Ni20A coating. The presence of compressive residual stress is expected to help in mitigating the generation and propagation of cracks.

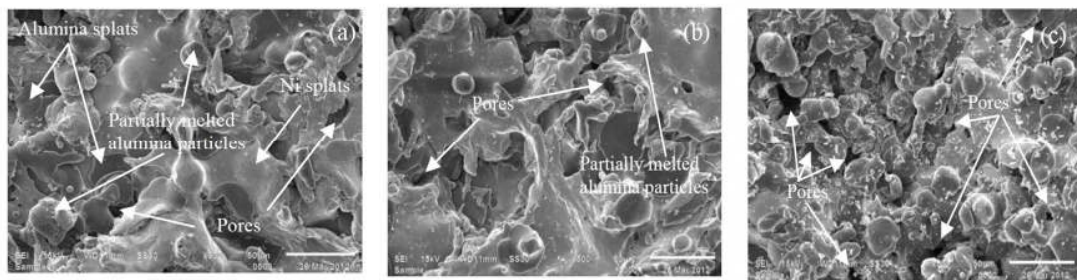


Fig. 2. Surface SEM micrograph of flame sprayed of (a) Ni + 20%Al₂O₃ (b) Ni + 40%Al₂O₃ (c) Ni + 60%Al₂O₃ coating deposited onto CA6NM steel [3]

Table 2. Various properties of flame sprayed Ni-Al₂O₃ coatings on CA6NM steel [3]

Coating	Coating Thickness (μm)	Microhardness (HV _{0.1} Kgf)	Fracture toughness (MPa√m)	Density (Kg/m ³)	Porosity (%)	Residual stress (MPa)	Coating Thickness (μm)
Ni20A	684 ± 38	563±90	1.4±0.11	7100±100	1.3±0.20	-122±14	684 ± 38
Ni40A	628 ± 54	714±78	1.6±0.09	6350±68	1.8±0.16	-93±10	628 ± 54
Ni60A	583± 24	1151±108	0.9±0.12	5880±83	2.5±0.25	-31±6	583± 24

3.2. Slurry erosion

Slurry erosion performance of the coatings in comparison to bare steel is compiled in Fig 3. Loss of the material from the coatings and bare steel took place in an almost linear fashion. Erosion rates given as volume loss per unit time (mm³/min) shown in Fig 3b indicate that the coatings and the steel attained a steady state after a period of around 8 min. The variation in erosion rates with time indicates the absence of any incubation period. A high erosion rate observed in the initial stage begins to decrease gradually with time and after about 4 min of testing, erosion rates appears to stabilize. Further, it can be manifested that the coatings have reduced the erosion rates of the

bare steel. All the three coatings provided protection against slurry erosion in comparison to bare steel. Plot shown in Fig 4 compares the steady state erosion rates of the investigated materials. It can be observed that Ni40A coating showed lowest erosion rates in comparison to other coatings and steel. Ni40A coating showed 2 to 3 times lower erosion rates in comparison to bare steel. This might be due to presence of optimum combination of hardness and fracture toughness. Ni40A coating showed intermediate hardness and highest toughness as could be observed in Table 2. Thus, the microstructure of the coating, which has a controlling effect on these mechanical properties, showed a dominant role.

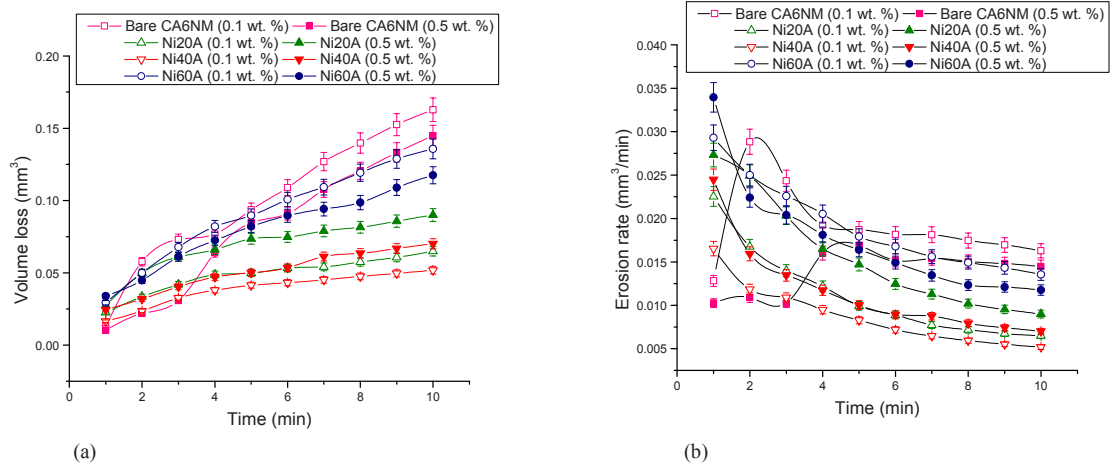


Fig. 3. Variation in the (a) volume loss and (b) erosion rates of bare and Ni-Al₂O₃ thermal sprayed coated CA6NM steel with time.

The variation of the erosion rates of the coatings and bare steel with concentration is also shown in Fig 4. It can be observed that the erosion rates of the test materials have shown a mixed response with an increase in concentration. The dependency of erosion rates on the concentration levels was analyzed using Eq (1).

$$E = KC^n \quad)$$

This would help in determining the level of dependency on concentration shown by target materials. A log-log plot between the erosion rates and concentration is shown in Fig 5. The slope of lines in Fig 5 would provide the value of exponent ‘n’ of Eq (1) which could help in estimating the level of dependency shown by a target material on concentration. It can be observed that although concentration was increased by 5 times, the erosion rates did not show similar response. Depending upon the target material, erosion rates increased by a factor of 0.9 to 1.3. This highlights the fact that with a rise in concentration the rate of increase of erosion rates decreases. Other investigators have also observed similar results, wherein, erosion rate has shown negative trend with a corresponding increase in concentration [5, 7, 9]. This might be due to the shielding effect of the rebounding particles. The rebounding particles would generate a shield, which could have interact with the incoming fresh particle. This incoming particle could be restricted from impacting the target material and/or the velocity of this particle could be serious retarded. Another possibility which could arise of the present situation is that the collision of the rebounding and incoming particle could result in change of the trajectory of the incoming particle making them to strike at an angle other than its initial set value. Secondly, depending upon the momentum and collision angles of the particles, there are possibilities of multiple impingements. The rebounded particle could be made to impact the target surface causing multiple impacts. Thus, it can be concluded that concentration has a complex role to play in the erosion process and require further in depth investigations.

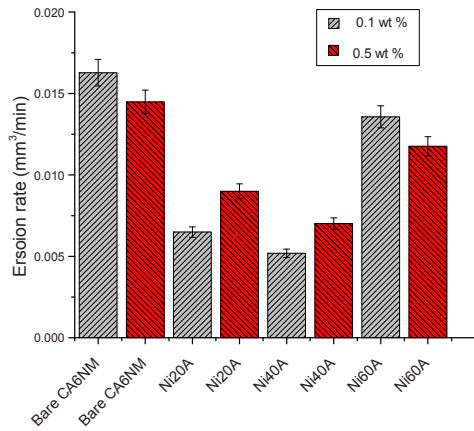


Fig. 4. Effect of concentration on steady state erosion rates of bare and thermal thermal sprayed Ni-Al₂O₃ coated CA6NM steel

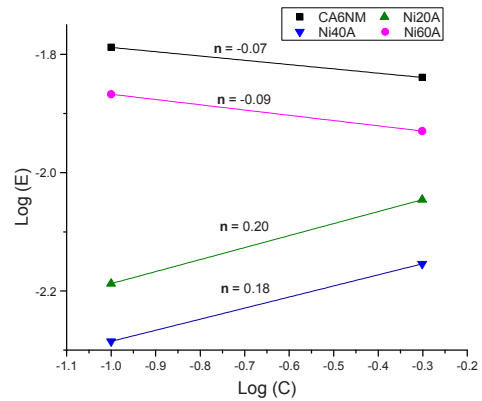


Fig. 5. Value of exponent 'n' according to Eq (1) for bare and sprayed Ni-Al₂O₃ coated CA6NM steel

3.3. Slurry erosion mechanism

Slurry erosion mechanism of the coatings showed a little dependency on the concentration of erodent particles. SEM micrographs of only Ni-Al₂O₃ coatings eroded at 0.5 wt % concentration condition have been illustrated in Fig 6. The erosion mechanism was more or less similar for each coating. Further, it was also observed that erosion rate was not affected by exposure time. The major factor which appears to control the erosion mechanism was the alumina content. It could be analyzed from the SEM micrographs of the eroded surface that the tendency of the coating to be removed due to fracturing of alumina splats increased with an corresponding increase in alumina content. Ni60A coating containing maximum proportion of alumina showed highest presence of fractured splats. Other than this mechanism, removal of material in form of splats was a dominant factor, which controlled the erosion mechanism of the coatings. Some marks of micro-cutting were also observed for Ni20A coating, however, such marks were not prominent enough in other coatings. In case of base steel, platelet mechanism combined with ploughing and microcutting was observed to be the dominant erosion mechanism.

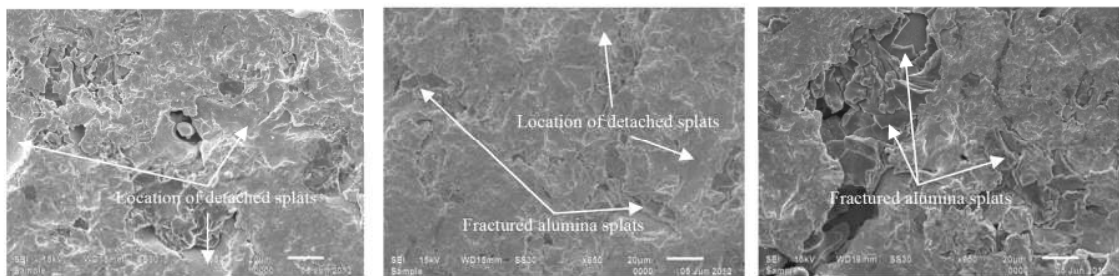


Fig. 6. SEM micrographs of thermal sprayed (a) Ni + 20% Al₂O₃ (b) Ni + 40% Al₂O₃ and (c) Ni + 60% Al₂O₃ coatings eroded at 16 m/s, 90° impingement angle and 0.5 wt % of sand particles.

4. Conclusions

Ni-Al₂O₃ based thermal spray coatings were developed by mixing alumina in different proportions. Slurry erosion behavior of these coatings was investigated using two different levels of concentration of sand particles. From the study, it can be concluded that:-

- All the coatings (Ni + 20, 40 and 60 wt. % Al_2O_3) investigated in the present work showed significant improvement in the erosion resistance of bare CA6NM steel
- Ni+40wt. % Al_2O_3 coating showed the highest resistance against slurry erosion
- Although with an increase in concentration, the erosion rates of the test materials increased; however, the accretion was not as proficient as the increase in concentration level. This highlights the important role played by shielding layer formed by rebounding particles.
- Erosion mechanism was dominantly controlled by the presence of alumina. The effect of concentration of erodent particles was not significant on the erosion mechanism. Fracturing of alumina splats and removal of material in form of splats were the dominant mechanism responsible for the erosion of coatings.

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