EFFECT OF CARBON NANOTUBES ON EROSION WEAR PROPERTIES OF NICR COATINGS ON TURBINE STEEL UNDER HYDRO ACCELERATED CONDITIONS

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ABSTRACT

In this research paper, slurry erosion behaviour of carbon nanotubes (CNT) reinforced NiCr coatings on turbine steel has been evaluated under hydro dynamic experimental conditions. The slurry erosion behaviour was evaluated at different combination of experimental parameters viz. average particle size, speed (rpm) and slurry concentration. The experiments were performed with help of slurry erosion test rig on uncoated and coated turbine steel alloy 13Cr4Ni specimens. The surface roughness, porosity and microhardness of as coated samples were measured. The results indicated that the velocity, impact angle and slurry concentration were the most significant among various parameters, influencing the wear rate of these coatings. The average particle size showed least significant effect on both the coatings. The carbon nanotubes reinforced NiCr coating showed better erosion resistance than other specimens at all experimental conditions due to better interlocking of CNT with NiCr coating matrix.

KEYWORDS: Turbine steel, hardness, erosion, hydropower, turbine.

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1. INTRODUCTION

The erosive wear of metal parts of hydro-turbines is a common problem in hydro power plants [1, 2]. The erosion is caused by suspended silt particles in flowing river water, which strikes the turbine blades, and it reduces its performance over the time span [3]. During rainy seasons, this problem becomes more serious due to heavy silt in the water. It causes the alteration in configuration of turbine parts, leading to continuous mass loss and decreases the power generating capacity of the plants. It subsequently leads to shut down of plants for maintenance and enhances economic losses [4].

Stainless steels are mostly used in hydroelectric power plants due to higher corrosion resistance [5]. Because of their lower hardness, the performance level of these steels gets degraded when subjected to various hydrodynamic conditions. Surface engineering techniques such as thermal spray coatings are widely used to develop hard and wear resistance coatings on these steels [6-8]. Among the various thermal spray coatings, HVOF spray coating is widely used because of its higher velocity, lower temperature operation than plasma spraying and lesser dwell time, which results in a dense coating structure with good bond strength, higher hardness, lesser decarburization, lower porosity and oxide content [9-12]. The study of literature reveals that many authors have developed various types of coatings viz. WC-Co-Cr coatings, Ni-TiO₂, Cr₃C₂, NiCr, Cr₂O₃-50%Al₂O₃ coatings, CoNiCrAlY coatings, Al₂O₃ on stainless steels to enhance the erosion resistance of hydro turbine steels under hydro dynamic conditions [2, 5, 6, 8, 13-15].

The carbon nanotubes (CNT) were invented and developed by Iijima in 1991 [16]. These have produced enormous research enthusiasm for their applications in engineering sciences. This is because of their exceptional physical and substance properties, for example, high strength, high stiffness and low density. CNT are hundreds of times stronger than all types of steels and also have many times high tensile modulus than that of steel [17, 18]. With exceptional mechanical properties including strength, modulus, stiffness which exceeds all types of materials, CNT offer tremendous opportunities for the development of fundamentally new CNT reinforced metal matrix or metal ceramics composite materials for applications in 21st century [19, 20]. The thermal sprayed coating is a porous material which has many local micro-cracks or through pores, and it is coated on a rough surface [21, 22]. These defects create paths for corrosive fluids or aggressive chemicals to attack the substrate steels [23-25]. This attack causes the changes in microstructure with the formation of oxide layer. The severe formation of oxide layer has been reported as principle reason behind the failure of thermal spray coatings [26]. Carbon nanotubes are nanoparticles; therefore these can easily enter and fill these pores and can act as a barrier to the erosive wear.

The aim of this experimental investigation was to study erosion behaviour of CNT reinforced NiCr coatings on turbine steel for providing resistance against slurry erosion under hydrodynamic conditions. The high velocity oxy fuel (HVOF) thermal spraying process has been used to develop the coatings due to its versatility and in-situ application possibilities. The 13Cr4Ni turbine steel alloy was selected as substrate material because this material is being used to manufacture turbine components in India. The study shall provide significant information regarding slurry erosion performance of HVOF sprayed CNT reinforced NiCr coatings on 13Cr4Ni grade of ASTM A743 turbine steel. No such information has been reported in the open literature on these coatings-material combinations under hydrodynamic conditions, which are very similar to the actual hydraulic power plant environments.

2. MATERIALS AND METHODS

Deposition and Evaluation of as-Coated Turbine Steel

13Cr4Ni turbine steel was selected as substrate material. The actual composition of this steel (wt. %) included C (0.04%), Mn (0.68%), Si (0.21%), P (0.20%), S (0.45%), Cr (13.68%), Ni (4.90%), Mo (0.45%), Fe (Balance). Commercial NiCr powder (Make: H.C.Starck Germany, particle size $45 \pm 10 \mu\text{m}$) was mixed with 5 wt.% carbon nanotubes powder in a ball mill. The HVOF thermal spraying technique was used to deposit the NiCr and 5 wt.% CNT-NiCr composite powders on turbine steel samples at Metalizing Equipment Company Pvt. Ltd., Jodhpur. The steel samples were polished with SiC papers and were shot blasted with alumina powder before deposition of coating powders. Minitest-2000 thin film thickness gauge was used to measure coating thickness during the spraying process. Surface roughness of each coated specimen was measured with surface roughness meter SJ-210. Microhardness of the specimens was measured along the coating cross-section. The samples were cut using diamond cutter to expose cross-section before measuring the hardness. Image analyzer software was used to evaluate the porosity of the coated specimens.

Slurry Erosion Experiments

The slurry erosion experiments were performed on test rig available at Department of Mechanical Engineering, Punjabi University Patiala. The schematic diagram of the test rig is shown in Figure 1. The centrifugal pump of test rig was operated with a 1500 rpm, 5HP motor. Slurry was procured from Bhakhra Nangal Power Plant, Himachal Pradesh, India. It consisted of main constituent of SiO_2 with average hardness of 1140 Hv. Two concentrations of slurry were prepared viz. 15000 ppm, and 30000 ppm. Each cycle of experiment was performed for 60 minutes, and total six cycles of one hour duration each were performed. The weight change of the specimens was measured with electronic weight balance having 0.1 mg resolution after

each cycle. Fresh slurry was prepared for each experiment cycle. The data for each test was compiled to calculate the cumulative mass loss per unit surface area.

Figure 1: Jet erosion tester Schematic diagram [27]

Experimental Design

In the present investigations, based on previous studies, three parameters viz. speed, particle size and slurry concentration were selected because these parameters significantly affect the slurry erosion rate [2, 28]. Taguchi's L4 orthogonal array, as shown in Table 1 has been selected with two levels of each parameter. Two levels of particle size viz. 100 μm and 200 μm were selected, two levels of slurry concentration viz. 15000 ppm, and 30000 ppm were selected and two levels of speed (rpm) viz. 2500 rpm and 5000 rpm were selected to perform this experimental work. Four experiments were performed for each uncoated 13Cr4Ni turbine steel samples, NiCr and 5 wt.% CNT-NiCr coated 13Cr4Ni turbine steel samples. Total twelve were conducted in this research work

Table 1: L4 Orthogonal Array of Taguchi Method for Experimentation Design

Experiment no.	Concentration (in ppm)	Particle size (in μm)	Speed (in rpm)
1	15000	100	2500
2	30000	200	2500
3	15000	200	5000
4	30000	100	5000

3. RESULTS

Mechanical properties of NiCr and 5 wt.% CNT-NiCr coatings

The coating thickness, surface roughness and porosity of as sprayed NiCr and 5 wt.% CNT-NiCr coatings were evaluated and have been displayed in Table 2. The averages of 5 measurements have been taken for both types of coatings. The average coating thickness for both conventional and nano-composite coating was found to be 250 μm . The average surface roughness for NiCr coated turbine steel was found to be 2.94 μm and that for 5 wt.% CNT-NiCr coated steel was found to be 2.60 μm . The addition of CNT in the NiCr coating led to formation of dense coating with lower porosity. The CNT were able to fill the pores in NiCr coating matrix, which has led to decrease in porosity and surface roughness of the coating microstructure.

Table 2: Thickness, Surface Roughness and Porosity of Coatings

Type of Coating	Thickness (μm)	Surface roughness (μm)	Porosity (%age)
NiCr coated turbine steel	250	2.94	3.2
5 wt.% CNT-NiCr coated turbine steel	250	2.60	2.9

The microhardness profiles along the cross section of the HVOF sprayed NiCr and 5 wt.% CNT-NiCr coatings on 13Cr4Ni turbine steel are shown in Fig. 2. The average microhardness value of 13Cr4Ni substrate was found to be equal to 245 Hv, and that for NiCr specimens was in the range of 770-792 Hv. The microhardness value for HVOF sprayed 5 wt.% CNT-NiCr coated specimen was in the range of 1012 to 1095 Hv. The average microhardness for 5 wt.% CNT-NiCr coated steel specimens was found to be more than that for NiCr coatings. The microhardness of CNT reinforced coating was due to decrease in porosity along with surface roughness, which has closed the pores in NiCr matrix, and enhanced resistance to indentation.

Figure 2: Microhardness Profiles along the Cross Section of NiCr and 5 wt.% CNT-NiCr Coatings on 13Cr4Ni Turbine Steel

Comparison of Erosion Performance

The uncoated, NiCr coated and 5 wt.% CNT-NiCr coated turbine steel specimens were subjected to slurry erosion experiments in the slurry erosion test rig. The erosive wear rate has been evaluated in terms of mass loss per unit area for all experimental conditions. The erosion graphs during the experimentation for uncoated, and NiCr and 5 wt.% CNT-NiCr coated specimens are shown in Figure 3, Figure 4 and Figure 5 respectively. The uncoated 13Cr4Ni turbine steel underwent highest rate of erosion rate in all four hydrodynamic conditions. The maximum erosion rate was observed at experiment number 4 at slurry concentration 30000 ppm, particle size 100 μm and velocity 5000 rpm, whereas, for experimental conditions number 1, the erosion rate was minimum at slurry concentration 15000 ppm, particle size 100 μm and velocity 2500 rpm for all types of specimens. The erosion rate of 5 wt.% CNT-NiCr coated turbine steel was minimum for all experimental conditions in comparison to all other types of specimens. This may be attributed to the addition of CNT in the NiCr coating matrix, which had increased microhardness of the as-sprayed coating by decreasing porosity and surface roughness.

The cumulative mass loss (in mg/cm^2) for all four experimental conditions after six hours of erosion testing of uncoated, NiCr coated and 5 wt.% CNT-NiCr coated turbine steel has been shown in Figure 6. The 5 wt.% CNT-NiCr coatings was able to reduce mass loss significantly as compared to other types of specimens.

Figure 3: Erosion Curves for Uncoated 13Cr4Ni Samples

Figure 4: Erosion Curves for NiCr Coated 13Cr4Ni Samples

Figure 5: Erosion Curves for 5 wt.% CNT-NiCr Coated 13Cr4Ni Samples

Figure 6: Cumulative Mass Loss for Uncoated, NiCr Coated and 5 wt.% CNT-NiCr Coated 13Cr4Ni Turbine Steel

Effect of Various Parameters on Slurry Erosion

(i) Effect of Slurry Concentration

The effect of different slurry concentrations on mass loss of uncoated, NiCr coated and 5 wt.% CNT-NiCr coated 13Cr4Ni turbine steel is shown in Figure 7. For both types of slurry concentrations i.e. 15000 ppm and 30000 ppm, the 5 wt.% CNT-NiCr coating imparted better erosive resistance to the turbine steel as compared to NiCr coating, whereas uncoated 13Cr4Ni specimen was having highest cumulative mass loss at both levels of slurry concentrations. At 15000 ppm, 5 wt.% CNT-NiCr coating was able to reduce mass loss of uncoated steel by 61.25%, and at 30000 ppm, this coating was able to reduce mass loss of uncoated steel by 54.13%. The might be attributed to uniform dispersion of CNT in NiCr coating matrix which has

led to increase in hardness of coating matrix. With increase in slurry concentration, the mass loss of uncoated and both types of coatings increased, which might be attributed to the increase in severity of abrasive attack as a greater number of sand particles were impinging on the surface.

(ii) Effect of Speed

The experiments were performed at two levels of speed viz. 2500 rpm and 5000 rpm. The effect of two speeds on overall mass loss for uncoated, NiCr coated and 5 wt.% CNT-NiCr coated 13Cr4Ni turbine steel samples is shown in Figure 8. For both types of speeds, the 5 wt.% CNT-NiCr coating imparted better erosive resistance to the turbine steel as compared to NiCr coating, whereas uncoated 13Cr4Ni specimen was having highest cumulative mass loss at both levels of speed of rotor. At 2500 rpm, 5 wt.% CNT-NiCr coating was able to reduce mass loss of uncoated steel by 55.80%, and at 5000 rpm, this coating was able to reduce mass loss of uncoated steel by 56.69%. The might be attributed to uniform dispersion of CNT in NiCr coating matrix which has led to increase in hardness of coating matrix. With the increase in speed of rotor from 2500 rpm to 5000 rpm, the kinetic energy of slurry particles increased, which might have led to increase in mass loss by impacting particles. Both types of coatings were able to reduce the mass loss of turbine steel by about 40-60%.

(iii) Effect of Average Particle Size

The influence of average particle size on the mass loss of uncoated, NiCr coated and 5 wt.% CNT-NiCr coated 13Cr4Ni turbine steel is shown in Figure 9. The two levels of particle size were selected for this study viz. 100 μm and 200 μm , and it was found that at each level, 5 wt.% CNT-NiCr coated steel showed better erosion resistance than NiCr coated turbine steel. At 100 μm particle size, 5 wt.% CNT-NiCr coating was able to reduce mass loss of uncoated steel by 47.69%, and at 200 μm particle size, this coating was able to reduce mass loss of uncoated steel by 54.77%. The might be attributed to uniform dispersion of CNT in NiCr coating matrix which has led to increase in hardness of coating matrix. The mass loss increased with increase in particle size, and this might be due to increase in surface area of particles, and with increase in surface area, the particles were able to erode more material from the surface of specimens.

Figure 7: Effect of Slurry Concentration on Slurry Erosion of NiCr Coated and 5 wt.% CNT-NiCr Coated 13Cr4Ni Turbine Steel

Figure 8: Effect of Speed on Slurry Erosion of NiCr Coated and 5 wt.% CNT-NiCr coated 13Cr4Ni Turbine Steel

Figure 9: Effect of Particle Size on Slurry Erosion of Uncoated, NiCr Coated and 5 wt.% CNT-NiCr Coated 13Cr4Ni Turbine Steel

Figure 10: SEM Micrograph of Uncoated Steel Specimen after Erosion at Slurry Concentration 30000 ppm, Particle size 100 μ m and velocity 5000 rpm

Figure 11: SEM Micrograph of NiCr Coated 13Cr4Ni Turbine Steel Specimen after Erosion at Slurry Concentration 30000 ppm, Particle size 100 μ m and Velocity 5000 rpm

Figure 12: SEM micrograph of 5 wt.% CNT-NiCr coated 13Cr4Ni Turbine Steel Specimen after Erosion at Slurry Concentration 30000 ppm, Particle size 100 μ m and Velocity 5000 rpm

4. DISCUSSION

In this experimental work, NiCr and 5 wt.% CNT-NiCr coatings have been successfully deposited on 13Cr4Ni turbine steel by HVOF thermal spraying technique. The coatings formed were homogenous, dense and were free from any cracks. The coating thickness was found to be 250 μ m for both NiCr and CNT reinforced NiCr coating. The porosity of NiCr coating was 3.2, which further reduced to 2.9 with addition of CNT in NiCr coating matrix. The decrease in porosity of with addition of CNT in NiCr coating matrix might be attributed to uniform dispersion of CNT in the coating matrix, which has led to uniform melting of NiCr powder particles. The CNT were able to transfer heat between NiCr particles due to their high thermal conductivity, and which resulted in densely packed NiCr coating matrix. The surface roughness of NiCr coated specimen was 2.94 μ m and that of 5 wt.% CNT-NiCr coated specimen was 2.60 μ m. The uniform melting and solidification of NiCr particles due to addition of CNT has resulted in decrease in surface roughness of coating surface. Therefore, the addition of CNT in NiCr coating has successfully improved the coating microstructure by improving surface roughness and reducing porosity of the coating. Goyal, et al. [29] have revealed that CNT were uniformly distributed throughout the composite matrix, and formed a bridge-like structure between the splats of chromium oxide, which improved the properties of composite coating. Rao, et al. [4] have revealed that decrease in porosity gives a smooth surface of thermal spray coatings, and that might be the reason of lower surface roughness of 5 wt.% CNT-NiCr coating as compared to NiCr coating.

The average microhardness value of 13Cr4Ni substrate was found to be equal to 245 Hv, and that for NiCr specimens was in the the range of 770-792 Hv. The microhardness value for HVOF sprayed 5 wt.% CNT-NiCr coated specimen was in the range of 1012-109545 Hv. The average microhardness for 5 wt.% CNT-NiCr coated steel specimens was found to be more than that for NiCr coatings. The increase in microhardness of 5 wt.% CNT-NiCr coating might be due to the improvement in inter-splat bound strength, resulting from the strong reinforcement by uniform dispersion of CNT in

the NiCr coating matrix might be the reason of higher hardness of 5 wt.% CNT-NiCr coated steel specimens [29-32].

The slurry erosion experiments were performed under different experimental conditions similar to that of actual hydro turbine environment. The results indicated that uncoated 13Cr4Ni turbine steel was having highest erosion rate as compared to NiCr and 5 wt.% CNT-NiCr coated turbine steel. The irregular micro-hills on the surface of uncoated steel specimen might have attributed to highest mass loss during initial hours of experimentation. The scanning electron micrograph of eroded uncoated steel specimen revealed the presence of large number of impact marks. The deep craters, plastic deformation and platelet mechanism has caused highest mass loss of uncoated steel.

The thermal spray coatings has caused increase in microhardness of specimen, and this has caused reduction in mass loss during slurry erosion of coated steel specimens [33]. The erosion rate was increased with increase in speed of rotor, increase in slurry concentration and increase in particle size of impacting particles. Increasing the sand concentration has led to increase in the severity of erosive attack as a greater number of sand particles with greater number of cutting edges impinged on the surface of specimens during slurry erosion tests [28, 34]. In case of NiCr coated specimen, the craters were found in scanning electron microscopy analysis. Plastic deformation and microcutting was the reason of material loss from the surface of NiCr coated specimen.

The 5 wt.% CNT-NiCr coated steel specimens were found to have lowest material removal rate due to higher hardness, and better surface properties in comparison to NiCr coated steel specimens under all experimental conditions. Scanning electron microscopy of eroded CNT reinforced NiCr specimen revealed microcutting, and microchipping for lower material loss in comparison to other types of specimens. Jambagi and Bandyopadhyay [35] and Balani, et al. [36] reported that carbon nanotubes first improves the microhardness, surface roughness and porosity of coating, and then it binds splats together and improves coating cohesion, thereby increasing the erosive wear resistance of coating.

5 CONCLUSIONS

The following conclusions are made from the present research work:

- NiCr and 5 wt.% CNT-NiCr powders were successfully deposited on 13Cr4Ni turbine steel by HVOF process.
- 5 wt.% CNT-NiCr coating was found to have higher microhardness, better surface finish and lower porosity than NiCr coating due to uniform dispersion of CNT in NiCr coating matrix. This has also led to uniform melting and solidification of composite coating matrix.
- Both NiCr and 5 wt.% CNT-NiCr coated samples were found to have significantly better slurry erosion resistance than uncoated 13Cr4Ni steel samples due to high hardness of coatings.
- The deep craters, plastic deformation and platelet mechanism has caused highest mass loss of uncoated steel. Scanning electron microscopy of eroded CNT reinforced NiCr specimen revealed microcutting, and microchipping for lower material loss in comparison to other types of specimens.
- 5 wt.% CNT-NiCr coating was found to have highest resistance to slurry erosion under all experimental conditions. For comparison between the erosion rates of all the coatings, the following order of erosion rate was observed.

5 wt.% CNT-NiCr coated 13Cr4Ni < NiCr coated 13Cr4Ni < Uncoated 13Cr4Ni

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