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RESEARCH ARTICLE

Analysis for Sliding Wear performance of Thermally Sprayed Ceramic Oxides Coated Low Alloy Steel

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ABSTRACT

Wear is one of the most common problems encountered in many industrial applications such as shaft sleeve failure, piston rod failure in reciprocating pump etc. Thermal sprayed ceramic coatings have been widely employed to offer alternative for modifying the component surface properties in a broad range of industrial applications, primarily for wear resistance and corrosive environment. The aim of the work is to develop ceramic oxides coatings on low alloy steel substrate through plasma spraying route and to investigate the sliding wear behavior of various ceramic oxides coating along with the uncoated specimen with respect to various load, sliding speed and sliding distance and to generate empirical relationship for the prediction of coatings wear rate. In the present investigation, ceramic oxide coatings of Al2O3 + 40% TiO2 and Cr2O3 were developed on low alloy steel substrate through plasma spaying route. The samples are characterized by SEM and micro hardness measurements. Further, the samples are subjected to sliding wear test by following a plan of experiments, based on the Taguchi technique, which is used to acquire the sliding wear test data in a controlled way using Pin-On-Disc test setup as per ASTM G99 standards. The sliding wear tests revealed that the wear rate was significantly reduced in Cr2O3 coated samples followed by Al2O3 + 40% TiO2 coated samples as compared to base metal (substrate). The ANOVA test revealed that, load is the most influential among various factors influencing the wear rate of these coatings. The experimental results were used to develop empirical model using MINITAB 16 successfully. The prediction of these models shows less error with experimental result.

1 Introduction

In the modern industrial world, engineering components are being subjected to increasingly demanding environments. This has made the components prone to more rapid degradation due to mechanisms such as wear, corrosion, oxidation or failure under high heat load. To fulfill numerous industrial applications, an effort to achieve enhanced performance in terms of productivity and efficiency, surface treatment technologies have been attracting a great deal of attention as they

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present a cost effective way to combat degradation modes such as the above without sacrificing the bulk properties of the component material. Among the entire surface phenomenon, the problem of wear is of high concern in most of the industrial components such such as shaft sleeve failure, piston rod failure in reciprocating pump etc. (Ramesh et al, 2011). Various surface modifications technologies are now available. Among them, thermal spraying, which refers to a family of material deposition techniques, has emerged as an important tool of increasingly sophisticated surface engineering technology (Sidhu et al, 2005). Plasma spray coating is identified as the most flexible and versatile thermal spray process with respect to the sprayed materials. Almost any material can be used for plasma spraying on almost any type of substrate. The high temperature of plasma spray processes permits the deposition of coatings for applications in areas of liquid and high temperature corrosion and wear protection and also special applications for thermal, electrical and biomedical purposes. Plasma spraying can spray very high melting point materials such as super alloys and ceramics. Further, it offers a wide range of quality and cost effective coatings and hence can be exploited as one of the attractive means of substituting for expensive scarce materials (Ramesh et al, 2011). In the light of the above, present investigation is aimed at development of plasma sprayed ceramic oxides coatings on AISI 4140 steel substrate. The developed coatings along with uncoated specimen were subjected to dry sliding wear tests with respect to various loads, sliding speed and sliding distance and empirical relationship were generated for the prediction of coatings wear rate.

2 Experimental Details

2.1 Materials

AISI 4140 steel (a low alloy steel) was selected as a substrate material owing to its various industrial uses, such as in the pump shafts, shaft sleeve, valve stem, connecting rods etc. It possesses better through hardening and superior impact properties compared to plain carbon steels like 1045. The chemical composition of the substrate material was shown in table 1.

Table 1 Chemical composition of AISI 4140 (base metal)

Element	Weight %
Carbon	0.3954
Silicon	0.225
Manganese	0.785
Phosphorus	0.0187
Sulphur	0.0070
Chromium	0.166
Molybdenum	0.847
Nickel	0.0795

Commercially available ceramics oxides, namely aluminum oxide + titanium dioxide ($Al2O3$ + 40% $TiO2$) (Powder: Sulzer-Metco Amdry 6240, -35 +5 µm) and chromium oxide ($Cr2O3$) (Powder: Sulzer-Metco Amdry 6156, -35 +15 µm) powders are chosen as the coating material owing to its excellent wear and chemical inertness, high strength at ambient temperature for the enhancement of surface properties. For convenience, coating with $Al2O3$ + 40% $TiO2$ is referred as AT-40 and coating with $Cr2O3$ is referred as CR.

2.2 Material preparation

The AISI 4140 samples were prepared to the dimension of 10 mm diameter and 30 mm height. The substrates were cleaned using acetone solvent and grit blasted with garnet sand at the pressure of 700 kPa to attain proper roughness of the surface for good adherence of the coating.

2.3 Plasma spraying

Plasma spray deposition was carried out by using Air Plasma spraying technique (Make: Ion Arc, Coimbatore). The coating was performed by using optimized spraying parameters as specified in table 2 for achieving dense and uniform coating.

Table 2 operating parameter used for coating Deposition

Parameter	Range
Current (A)	500
Power (kW)	40
Voltage (V)	60 – 70
Plasma Gas flow rate Ar (lpm)	80
Career gas flow rate Ar (lpm)	40
Spraying distance (mm)	100

2.4 Characterization

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SEM (Scanning Electron Microscope) studies were conducted on samples to assess the microstructure uniformity and coating thickness of the developed coatings. Vickers micro hardness measurements were performed on a cross section of coatings with a load of 200 g and dwell period of 15 sec and average of three reading are tabulated in Table 3.

Table 3 Micro Hardness values

Specimen	**Vickers hardness number (HV)**	**% increase in surface hardness from base metal**
AT-40 Coating	852	64%
CR coating	1344	77%
AISI – 4140 (substrate)	307	--

The coating thickness was measured using SEM micrograph. The thickness of both the coating was approximately 250 µm as shown in the figure 1.

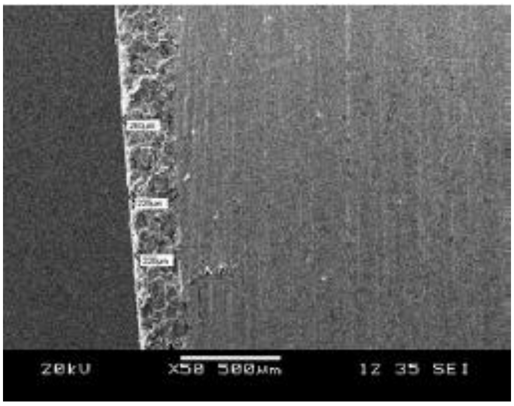

Figure 1 SEM micrograph of coating cross section

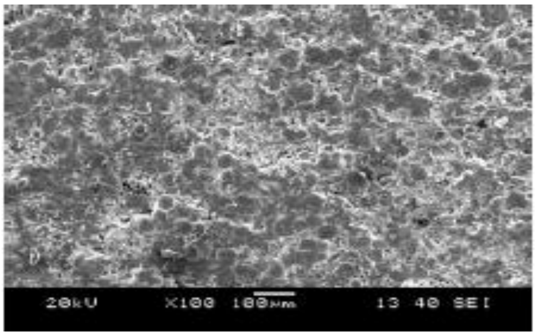

Figure 2 SEM micrograph of Al2O3 + 40% TiO2

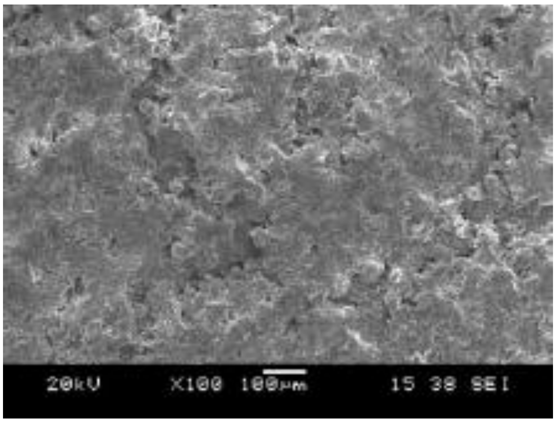

Figure 3 SEM micrograph of Cr coating 2O3

From figure 1, 2, 3 it is observed that, the deposition of coatings is uniform and dense. The interlayer bonding between the substrate and coating is clean and free of discontinuities with good adhesion.

2.5 Sliding wear test

Two body sliding wear tests were carried out on prepared coated specimens. Computerized pin-on-disc wear test machine (Make: DUCOM, Bangalore) was used for these tests. The tangential friction force and wear in microns were monitored with the help of electronic sensors and data acquisition software WINDUCOM 2010. These two parameters were measured as a function of load, sliding speed, sliding distance. The rotating disc was made of carbon steel of diameter 60mm and hardness of 64 HRC. Wear tests were carried out at room temperature without lubrication as per ASTM G99 standards.

2.5.1 Taguchi Technique

Taguchi method is a systematic application of design and analysis of experiments for the purpose of designing and improving product quality. The Taguchi method uses a special Orthogonal Array (OA) to study all the designed factors with a minimum of experiments (Magudeeswaran et al, 2014). Table 4 shows the control parameters investigated at the three experimental levels.

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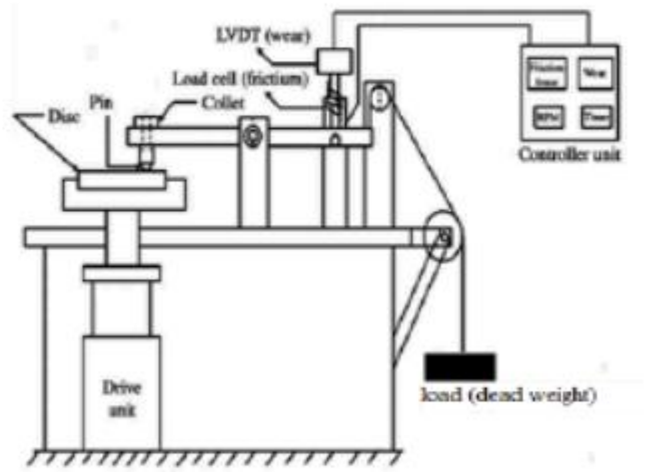

Figure 4 Schematic of Pin-On-Disc wear testing Machine

Table 4 Process parameters and their levels coating

Parameters	Levels		
	1	2	3
Load (N)	5	10	15
Sliding Speed (rpm)	300	400	500
Sliding Distance (m)	250	500	750

The OA experimental design method was chosen to determine an experimental plan (L9), because it is the most suitable for the conditions being investigated; for the three parameters and three levels with less experimental runs (Magudeeswaran et al, 2014). In this investigation, the wear tests were conducted as prescribed by the design matrix in a random order to prevent errors in the response. The wear rate was calculated through the mass loss method. The pin mass was measured before and after the test by means of a precision weighing machine (Make: Shimadzu; Japan. Model: AW 320) with 0.001 mg of resolution. The experimental output responses with design matrix are shown in Table 5. Regression model building technique was adopted to build a multiple linear regression model for coatings to predict the output responses based on experimentally measured values as shown in equation 1 & 2. Error less than 5 percent was observed between the predicted and actual wear rate. This indicates the adequacy of the model.

Wear rate of AT-40 (mm3/m)
= - 0.67 + 0.421 load (N) + 0.00911 speed (rpm) - 0.00777 sliding distance (m) **(1)**

Wear rate of CR (mm3/m)
= - 1.37 + 0.374 load (N) + 0.00866 speed (rpm) - 0.00666 sliding distance (m) **(2)**

3 Results and discussion

3.1 Analysis of variance (ANOVA)

The knowledge of the contribution of individual factors is critically important for the control of the final response. The ANOVA is a common statistical technique to determine the percent contribution of each factor for the experimental results (Magudeeswaran et al, 2014). The results of ANOVA for both the coating are shown in table 6 and 7. The ranking of process parameters generated by Taguchi method is shown in Table. 8. As inferred from Table 8, load was ranked as the highly influential process parameter followed by sliding distance and sliding speed for both the coatings.

3.2 Effect of load

Wear rates are calculated based on volume loss per unit of sliding distance. The wear loss values of the ceramic coatings increase with the increase in the applied loads as shown in figure 4. The magnitude of the normal load or the contact stress is important since it increases both the area of contact and the depth below the surface at which the maximum shear stress occurs as well as elastic or plastic deformation state (Ramachandran et al, 2012) With the inferences from the wear profiles (figure 5 & 6), it is evident that the wear rate and coefficientof-friction of ceramic coatings is much lower than that of substrate. Wear phenomenon of coating as well as substrate obeys the general three stages of wear process. The first stage consists of sudden increase in wear for a shorter period of time which is mainly due to abrasion between the asperities of top coat and rotating disc. The second stage comprises of steady state wear. In the third stage again there is a rise in wear and finally leads to failure. Further, the abrasive action of the detached particles entrapped in the contact area may significantly contribute to the material removal (Ramachandran et al, 2012).

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Table 5 Experimental Design matrix and Output Response

Experimental Run	Input parameters			Output Response: Wear rate x 10^{-3} (mm^3/m)		
	Load (N)	Sliding speed (rpm)	Sliding distance (m)	wear rate Cr_2O_3	wear rate Al_2O_3 + 40% TiO_2	wear rate of specimen
1	5	300	250	1.49	2.23	2.43
2	5	400	500	1.84	2.74	5.25
3	5	500	750	0.71	1.05	2.85
4	10	300	500	0.29	0.89	1.09
5	10	400	750	0.87	1.14	2.95
6	10	500	250	2.07	3.02	9.03
7	15	300	750	1.02	1.85	3.51
8	15	400	250	9.03	10.44	19.30
9	15	500	500	5.21	6.36	9.67

Table 6 ANOVA results for AT-40 coating

Source	DF	Seq SS	Adj SS	Adj MS	F	p	Contribution %
load (N)	2	38.378	38.378	19.189	10.10	0.090	48.23
speed (rpm)	2	14.732	14.732	7.366	3.88	0.205	18.514
sliding distance (m)	2	22.659	22.659	11.330	5.97	0.144	28.477
Residual Error	2	3.799	3.799	1.899			4.774
Total	8	79.568					100

Table 7 ANOVA results for CR coating

Source	DF	Seq SS	Adj SS	Adj MS	F	p	Contribution %
load (N)	2	30.111	30.111	15.055	6. 96	0.126	46.67
speed (rpm)	2	13.424	13.424	6.712	3.10	0.244	20.808
sliding distance (m)	2	16.651	16.651	8.326	3.85	0.206	25.81
Residual Error	2	4.326	4.326	2.163			6.705
Total	8	64.512					100

Table 8 Response table for means

Level	Al_2O_3 + 40% TiO_2 (AT-40)			Cr_2O_3 (CR)		
	Load (N)	Speed (rpm)	Sliding Distance (m)	Load (N)	Speed (rpm)	Sliding Distance (m)
1	2.006	1.654	5.230	1.3487	0.9324	4.1965
2	1.683	4.773	3.331	1.0743	3.9108	2.4447
3	6.216	3.477	1.344	5.0843	2.6641	0.8662
Delta	4.533	3.119	3.886	4.0100	2.9784	3.3303
Rank	**1**	**3**	**2**	**1**	**3**	**2**

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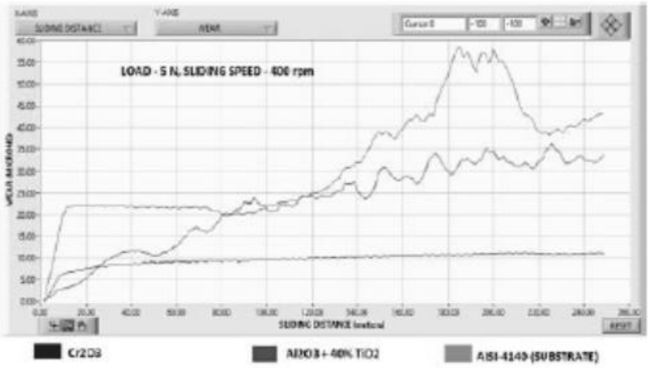

Figure 5 Wear profiles of coatings with Substrate

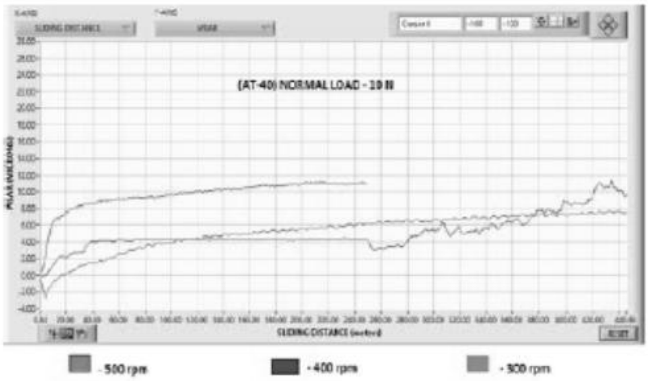

Figure 7 wear profiles of AT-40 coating under different sliding speed

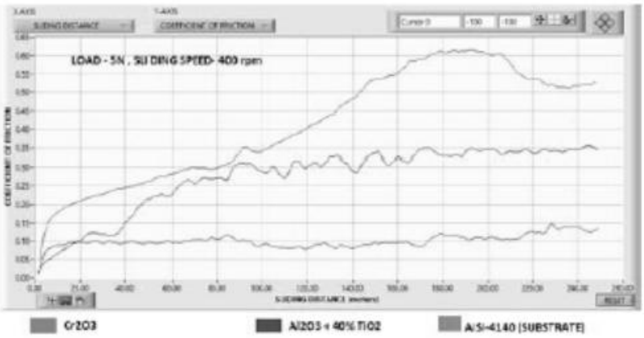

Figure 6 Coefficient-of-friction profiles of coatings with Substrate

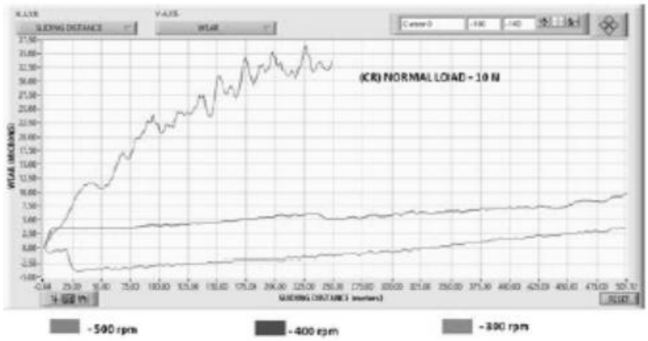

Figure 8 wear profiles of CR coating under different sliding speed

3.3 Effect of sliding speed

With the inferences from the wear profiles as shown in figure 7 and 8, it is evident that the wear rate of ceramic coatings is much lower than the wear rate of substrate and the wear will increase with the increase in sliding speed for both the coatings and substrate. Two kinds of results appear, depending on the speed: (1) In the case of low speed, plastic flow may take place and no brittle fracture happening to the asperity. (2) When the speed is high, the tangential impact effect will produce a brief extremely high stress inside the asperity and the asperity will be fractured as wear debris. The impact stress inside the asperity and consequently the fracture rate (wear rate) of the asperity will be proportional to the sliding speed (Ramachandran et al, 2012).

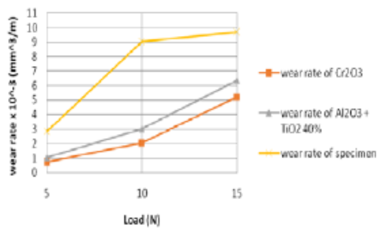

Figure 4 Load Vs Wear Rate plot

4 Conclusions

This investigation on sliding wear response of plasma sprayed Al2O3 + 40% TiO2 and Cr2O3 Analysis of sliding wear characteristics of the coatings has been done using Taguchi's design of experiment. Control factors affecting the sliding wear was identified through this method. Load is found to be most influential in accelerating wear, followed by sliding distance and sliding speed. Controlling this factor will significantly reduce the coating wear. coatings has led to the following specific conclusions.

• Empirical relationships were established using regression method to predict the wear rate of coatings.

• The sliding wear tests revealed that the wear rate was significantly reduced in Cr2O3 coated samples followed by Al2O3 + 40% TiO2

• Hardness has a strong control on wear resistance. Chromium oxide Cr coated samples as compared to base metal (AISI 4140).

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2O3 exhibits higher hardness than the Al2O3 + 40% TiO2 • Therefore the present investigation concludes that, ceramic oxide coatings can be effectively used to enhance the service life of components encountering wear problems. This leads to better wear resistance of coatings under various conditions.

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