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INVESTIGATION OF THE WEAR BEHAVIOUR OF AN AISI 1040 FORGED STEEL SHAFT WITH PLASMA-SPRAY CERAMIC-OXIDE COATINGS FOR SUGAR-CANE MILLS

RAZISKAVA OBRABE AISI 1040 KOVANE JEKLENE GREDI S KERAMIČNIMI OKSIDNIMI PREVLEKAMI ZA MLINE ZA MLETJE SLADKORNEGA TRSA

Duraisamy Revathi Ponnusamy Rajarathnam[1], Murugesan Jayaraman[2]

[1]Paavai Engineering College, Department of Mechanical Engineering, Namakkal District, India
[2]Velalar College of Engineering and Technology, Department of Mechanical Engineering, Erode District, India
drprajamalathi@yahoo.co.in

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In this investigation, ceramic oxide powders, alumina, titania, chromia, alumina-titania, alumina-chromia and titania-chromia, were coated for a thickness of 200 μm on an AISI 1040 forged steel substrate by means of an atmospheric plasma spraying method. Ni-Cr was used as an intermediate bond coat of thickness 20 μm over the substrate to improve the coating adhesion. Pin-on-disc apparatus was employed for a dry wear test as per the American Society for Testing and Materials G99 standards for a constant load of 10 N, at different sliding distances of 1000 m, 2000 m and 3000 m, respectively. The investigation shows that the microstructure, coating thickness, porosity, surface roughness and hardness influence the wear rate. Before and after the wear tests, surface roughness measurements were carried out by using a talysurf instrument on the specimens. It is shown that the highest value (20.89 μm) was obtained for the coating of alumina-titania. The practical results show that the pure chromia coated specimen has a very good wear-resistance property compared to the ceramic oxides. This suggests that surface coating with pure chromia on the top mill roll shaft of sugar industries enhanced the wear resistance.

Keywords: alumina, titania, chromia, atmospheric plasma spray, pin-on-disc, wear, Talysurf profilometer

V raziskavi so bili oksidni praški: glinica, titan, krom, aluminijev oksid, aluminij-krom, prevlečeni z 200 μm na AISI 1040 podlago kovanega jekla z metodo napševanja s plazmo. Ni-Cr smo uporabili kot vmesni vezni premaz z debelino 20 μm nad podlago za izboljšanje oprijemljivosti prevleke. Pin-on-disk aparat je bila uporabljen za preskus suhe obrabe, v skladu s standardi G99 Ameriškega združenja za testiranje in materiale, s konstantno obremenitvijo 10 N, na različnih drsnih razdaljah 1000 m, 2000 m in 3000 m. Preiskava je pokazala, da so mikrostruktura, debelina prevleke, poroznost, površinska hrapavost in trdota vplivali na stopnjo obrabe. Pred in po testih obrabe, so bile meritve vzorcev površinske hrapavosti izvedene z uporabo Talysurf instrumenta. Izkazalo se je, da je največja vrednost (20,89 μm), pridobljena s prevleko iz aluminijevega oksida-titanovega dioksida. Praktični rezultati kažejo, da ima s čistim kromom prevlečen vzorec zelo dobro odpornost na obrabo kot tisti s keramičnimi oksidi. Kaže, da površinska prevleka s čistim kromom na zgornji gredi mlina v sladkorni industriji poveča odpornost proti obrabi.

Ključne besede: aluminij, titan, krom, atmoferski plazma sprej, spoj na disk, obraba, Talysurf profilometer

1 INTRODUCTION

In many sugar industries, the top mill roller shaft, used to crush sugarcane, is made up of AISI 1040 forged carbon steel as this medium carbon, tensile steel shows good strength, toughness and wear resistance. The roller shaft has to operate under critical working conditions such as heavy load, high speed, temperature and chemical environment, while it crushes the raw sugar cane to extract the sugar cane juice. Hence, surface hardening of the shaft is a must to improve the wear resistance as they suffer from various types of degradation. Generally, the shaft diameter will decrease due to continuous rotation with a speed of 4 min^{-1} and accumulation of various impurities such as bagasse, ferrous and non-ferrous metals and also due to improper lubrications in between the journal bearing and the shaft. Hence, the shaft surface at the pinion end should be coated with ceramic materials with a good wear-resistance property.

The coating layer is very important because it enhances the wear resistance of the metal substrate of AISI 1040 forged steel to increase its life and efficiency. Some of the most commonly used ceramic materials in industrial applications are alumina (Al_2O_3), titania (TiO_2), Chromia (Cr_2O_3). S.-H. Yao[1] studied nanostructured Al_2O_3 with 13 % of mass fractions of TiO_2 coatings and found that they showed better performance in hardness and wear. Y. Sert et al.[2] studied the wear resistance of the plasma sprayed alumina – titania, titania, chromia and chromia – titania and found the effect of TiO_2 content on Al_2O_3–TiO_2 and Cr_2O_3–TiO_2 coatings on Al-based substrate, and concluded that hardness, coating density and wear resistance changed with the TiO_2 content.

B. A. Khan et al.[3] studied the microstructural, surface roughness and tribological properties of a coated specimen with alumina, titania and alumina-titania coating materials and the results showed that pure alumina has better wear properties than other coating materials, and it was observed that the thermal barrier coating decreases the wear rate compared to the parent metal. M. H. Korkut et al.[4] studied the wear behaviour of the ceramic surfaces over different test durations on AISI 1040 mild steel and found that the pure chromium III oxide (Cr_2O_3) has a higher wear resistance than pure Al_2O_3 and its compositions with TiO_2, they concluded that wear resistance decreased with an increase in the percentage of TiO_2 powder in Al_2O_3 mixture.

S. Islak et al.[5] investigated the effect of TiO_2 rate in an Al_2O_3–TiO_2 composite coating on SAE 1040 steel and observed that the phase transformations take place from stable α-Al_2O_3 and anatase TiO_2 to metastable γ-Al_2O_3, rutile TiO_2 and Al_2TiO_5 phase and as a result the microhardness value was found to be 3 to 4.5 times higher than that of SAE 1040 steel substrate materials due to a decrease in pore content when the TiO_2 powder rate increased in the composition. S. Salman et al.[6] investigated the thermal shock resistance of various ceramic oxides coated on a cast iron substrate and found that zirconia coated samples deformed at 1040 °C after 37 s when compared to Cr_2O_3 which deformed at 960 °C after 33 s. It was concluded that the Al_2O_3 coated specimen has less thermal shock resistance since it deformed at 920 °C in 31 s.

M. S. Kumar et al.[7] analyzed the tribological properties of thermally sprayed WC – 12 % of mass fractions of Co and Al_2O_3 – 13 % of mass fractions of TiO_2 on AISI 1040 steel used in the automobiles and found that the wear failure mechanism gets influenced more at higher temperatures around 600 °C. It was also observed that a carbide coating exhibited denser microstructured and higher hardness than ceramic oxide coatings. G. Bolleli et al.[8] investigated the wear behaviour of plasma-sprayed ceramic coatings (Al_2O_3, Al_2O_3 – 13 % of mass fractions of TiO_2 and Cr_2O_3) and found that the Cr_2O_3 coating was the hardest and most anisotropic among the other plasma-sprayed ceramics due to the low interlamellar cohesion, whereas the Al_2O_3 – 13 % of mass fractions of TiO_2 was less hard and tough due to the formation of a glassy phase and turns out to be quite brittle.

A. Prasad et al.[9] investigated the hardness of a Ni/La_2O_3 composite powder that was cladded over AISI 1040 steel through microwave irradiation to improve the wear resistance and observed the averaged Vickers microhardness was about 319HV. It was further stated that the hardness value depends upon the particle size, microwave power and microwave exposure time. M. S. Gök[10] studied the microstructure and abrasive wear performance of an AISI 1040 steel surface coated with different ceramic materials and observed that a higher rate of Cr_2O_3 in the composition produced a better and higher microhardness value than other ceramic coating materials. They also showed that increasing the proportion of TiO_2 in the composition affects the microhardness value of the specimen.

P. Gadhari et al.[11] studied the wear behaviour of a N-P-Al_2O_3 composite coating on AISI 1040 steel and showed that a change in the parameters like higher annealing temperature 500 °C and reducing agent concentration (25 g/L) improved the wear resistance of the coating. The amount of alumina content affects the wear resistance property of the composite coating. M. Yunus et al.[12] investigated the wear behaviour of ceramic coatings on a mild-steel substrate which has vast applications in aerospace, gas turbine engines and power generators. The result showed that the partially stabilized zirconia (PSZ) has more thermal barrier and thermal cycling resistance than alumina-titania and alumina. The coating temperature (1000 °C), types of coating and thickness of coating affect or influence the thermal barrier against the ceramic coating materials.

2 EXPERIMENTAL PART

2.1 Substrate preparation

AISI 1040 forged steel was used as a substrate material provided by M/s.Coimbatore Metal Mart. The substrate AISI 1040 forged steel was made into circular pins of 8 mm diameter and 30 mm length by performing turning and facing operations in the lathe machine from its original dimension of 30 mm diameter and 40 mm length. Three types of coating materials were used: ceramic oxide powders (99 % of mass fractions) Al_2O_3 as fused, primarily α-phase with particle -325 mesh size, (99 % of mass fractions) TiO_2 traces metal basis with particle – 325 mesh size, (98 % of mass fractions) Cr_2O_3 with particle size 5 μm provided by Sigma Aldrich Chemicals Pvt Ltd, Bangalore, India. The mixtures formed with six different compositions are shown in **Table 1**.

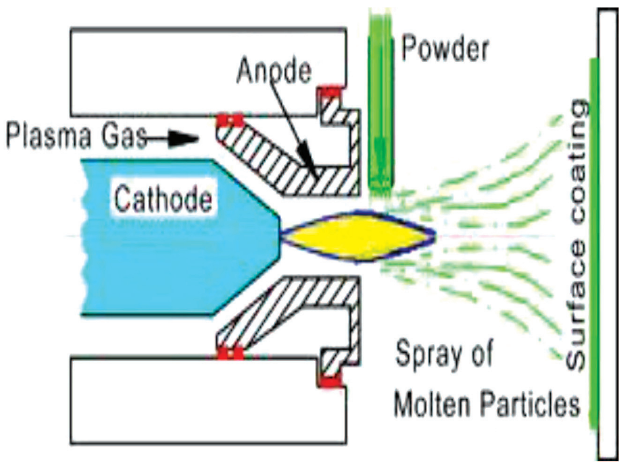

Figure 1: Schematic picture of plasma spray coating

Table 1: Chemical compositions (*w*/%) of ceramics for surface coating

Specimen No.	Al_2O_3	TiO_2	Cr_2O_3
S1	99	-	-
S2	-	99	-
S3	-	-	99
S4	45	55	-
S5	55	-	45
S6	-	45	55

Before spraying, the substrate was cleaned with acetone. In the present work NiCr bond coat of 20 µm thickness was deposited on the substrate surface materials so as to compose an intermediate surface for the purpose of best adhesion property and the coating thickness with 200 µm was deposited by plasma spraying process as shown in **Figure 1**.

2.2 Thermal spraying equipment

Sulzer Metco 3 MB spraying guns were used for the deposition of ceramic oxide layers provided by M/s. SprayMet Technologies Pvt Ltd, Bangalore, India. The parameters used for the deposition of ceramic oxide coatings by thermal spraying process are shown in the **Table 2**.

Table 2: Guidelines of plasma spray process

Gun	METCO 3MB
Nozzle	GH
Arc flow rate	80–90 L/min
Arc pressure	100–120 psi
Auxiliary gas flow rate	20–35 L/min
Auxiliary gas pressure	100 psi
Spray rate	2.0–6.5 kg/h
Arc voltage	60–70V
Arc current	490–590A
Spray distance	3–5 inches
Powder feed	40–50 grams/min

2.3 Characterization of coatings

The microstructures of the specimens coated with Al_2O_3, TiO_2, Cr_2O_3 and other compositions were characterized under a Scanning Electron Microscope (SEM) to study the microstructure of the substrate.

2.4 Microhardness of the ceramic oxide coatings

Hardness measurements were carried out to find the microhardness value of the AISI 1040 steel substrate and coated samples. The hardness test was carried out on the top surface of the coatings with a load of 250 g and dwell time period of 10 s and the average of three readings are shown in the **Table 3**.

Table 3: Hardness value of the specimen

Specimens	Vickers hardness number (HV)
AISI 1040	230
Al_2O_3	776
TiO_2	340
Cr_2O_3	960
45 % Al_2O_3 + 55 % TiO_2	448
55 % Al_2O_3 + 45 % Cr_2O_3	560
45 % TiO_2 + 55 % Cr_2O_3	652

2.5 Surface roughness measurements

Talysurf instrument schematic sketch shown in **Figure 2** was used to measure the surface roughness of the specimens before and after wear tests. The cut-off length was chosen as 0.8 mm for the instrument and a mean value of five readings was calculated.

2.6 Wear test and evaluation

Ceramic oxide coated specimens were subjected to dry wear tests by using a pin-on-disc wear testing device as per ASTM G99-04 standards. The 8 mm diameter and 30 mm length cylindrical pin samples coated with alumina, titania, chromia and combination of 45 % Al_2O_3 + 55 % TiO_2, 55 % Al_2O_3 + 45 % Cr_2O_3, and 45 % TiO_2 +

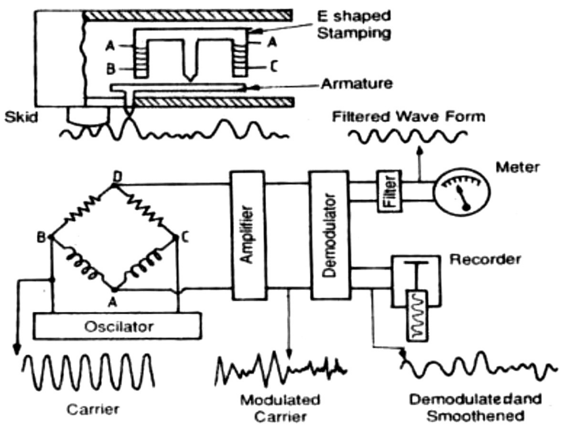

Figure 2: Schematic diagram of Talysurf instrument

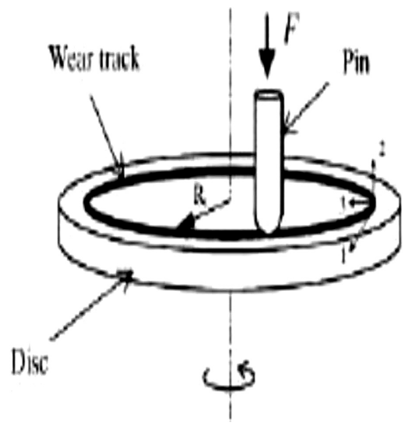

Figure 3: Pin-on-disc geometry

55 % Cr_2O_3 oxides of coating thickness 200 μm were used as test materials. Counter face material made from hardened steel was used as a disc. For each sample dry-sliding wear tests were carried out three times against a constant load of 10 N for a sliding speed of 260 min^{-1}, 525 min^{-1} and 790 min^{-1} under a sliding distance of 1000 m, 2000 m and 3000 m respectively. The corresponding weight losses of the coated specimens were calculated by means of an electronic weighing balance. The microstructural characteristics and wear behaviour were identified by means of the wear scars observed by using SEM for both the coated and uncoated specimens. The pin-on-disc geometry was shown in **Figure 3**.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Microstructure of ceramic oxide coating

Scanning Electron Microscope (SEM) images of the AISI 1040 forged steel substrate and ceramic oxide powder samples at 200× magnification are shown in **Figure 4**. **Figure 4a** shows various elements present in AISI 1040 forged steel substrate and the increase of the ferrite grain size at the inner regions and ferrite, for example, similar to white regions and perlite, for example, similar to dark side regions were found. **Figures 4b** to **4d** represent the morphological structure of the Al_2O_3, TiO_2 and Cr_2O_3 particles. The Al_2O_3 and TiO_2 powders have distinctive grain sizes, exhibited an irregular morphology and were sharp edged because of the agglomeration of essential particles.The alumina particles are generally nano-sized and the shape of particle is non-spherical. Particle density or true density gives data about the sort of material present in the sample. A particle density higher than 1.0 g/cc is attributed to a high alumina content in the sample rather than the organic matter. The porosity is likewise sensibly high as expected.[13] It demonstrates that the chromium oxide is in pure form and the particles are white colored nano-particles that are almost rhombohedral and isolated.

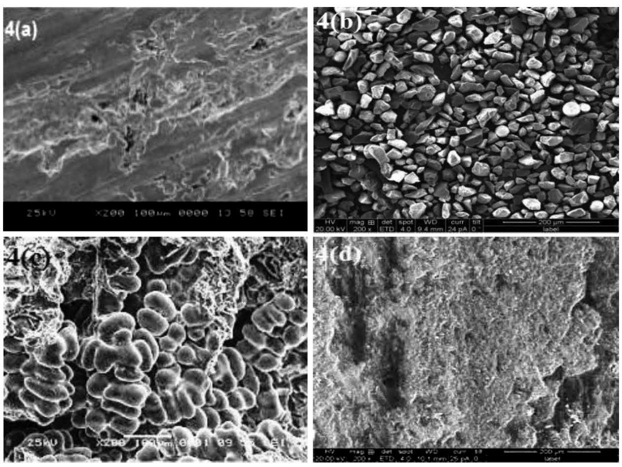

Figure 4: SEM images of steel substrate and ceramic oxides at 200× magnification: a) AISI 1040 forged steel, b) Al_2O_3, c) TiO_2, d) Cr_2O_3

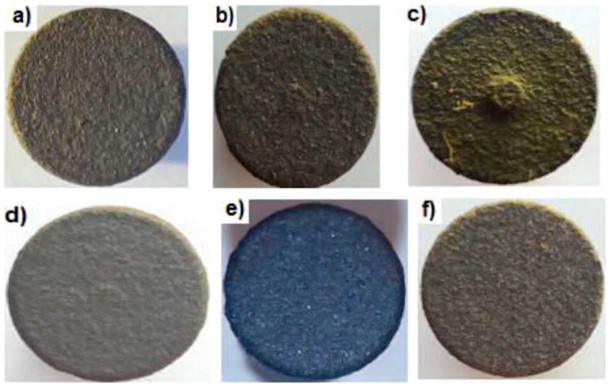

Figure 5: Photographic image of a) Al_2O_3, b)TiO_2, c) Cr_2O_3 d) 45 % Al_2O_3 + 55 % TiO_2, e) 55 % Al_2O_3 + 45 % Cr_2O_3 and f) 45 % TiO_2 + 55% Cr_2O_3

Photographic images of the ceramic oxide coated specimens on AISI 1040 forged steel substrate are shown in **Figure 5**. **Figure 5a** to **5f** show that the Al_2O_3, TiO_2, Cr_2O_3, 45 % Al_2O_3 + 55 % TiO_2, 55 % Al_2O_3 + 45 % Cr_2O_3 and 45 % TiO_2 + 55 % Cr_2O_3 particles are homogenously distributed with less porosity present on the surface of the specimens. An examination of these images revealed that the substrate surface layer and the ceramic coating layer were homogenously fused and there were no pores, cracks, and spaces on the coating area.

3.2 Surface-roughness measurement

The surface roughness (R_a) values were higher for both the coated and uncoated samples before the wear test, whereas the R_a values were lower for both the coated and uncoated samples after the wear test. The recorded values are shown in **Figure 6**. The specimen coated with 55 % Al_2O_3 + 45 % Cr_2O_3 and having a coating thickness of 200 μm is shows a smaller R_a value before the wear test when compared to other values of coated and uncoated specimens.The specimen coated with (99 % of mass fractions) TiO_2 and having a coating thickness of 200 μm shows a lower R_a value after the wear test when compared to the other values of the coated and uncoated specimens after the wear test.

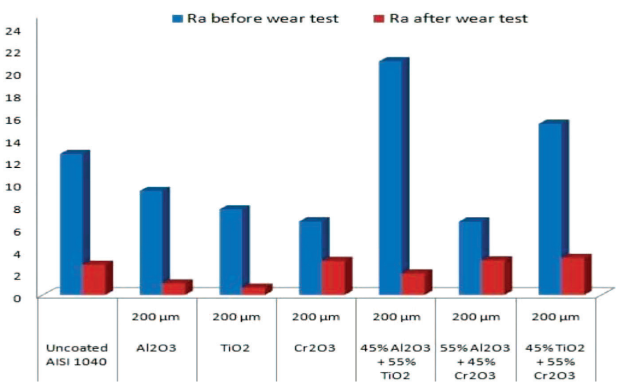

Figure 6: Surface roughness of coated and uncoated specimens

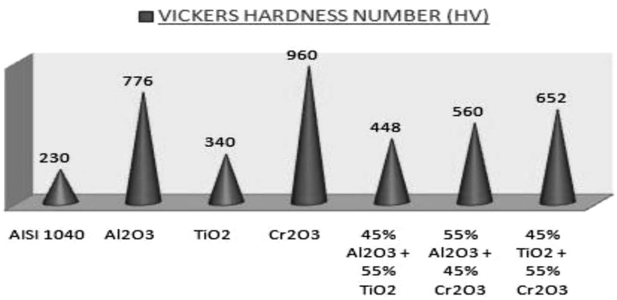

Figure 7: Microhardness of coated specimens and bare AISI 1040 forged steel

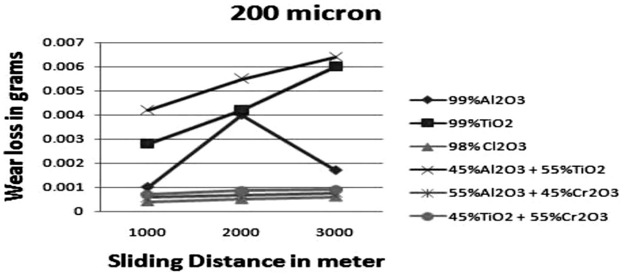

Figure 8: Effect of sliding distance on the wear loss for 200 μm

3.3 Microhardness values of ceramic oxide coating

Figure 7 shows the recorded microhardness values for different ceramic oxide coated and bare specimens. From the recorded values, the 99 % Cr_2O_3 coated specimen has the highest microhardness value when compared to the other coated and uncoated specimens.

3.4 Wear-rate performance of ceramic oxide coated specimens

By using a pin-on-disc apparatus, dry-sliding wear tests were carried out on the ceramic oxide coated and uncoated AISI 1040 specimens according to the ASTM G99-04 standard wear test. The effect of sliding distance in the wear loss of the uncoated and coated specimens at a constant load of 10 N for the different composition coating powder is shown in **Figure 8**.

The specimen coated with 99 % Cr_2O_3 and having a thickness 200 μm has comparatively less wear loss for all the sliding distances rather than the uncoated AISI 1040 forged steel specimen and other combinations of ceramic-oxide-coated specimens. The specimen coated with Al_2O_3-55 % TiO_2 shows a higher wear loss at all the sliding distances when compared to all the other coated specimens. SEM images of ceramic oxide coated specimens and AISI 1040 forged steel after wear test under a constant load of 10 N are shown in **Figures 9**. From **Figure 9a** to **9f** it was observed that the Al_2O_3-55 % TiO_2 coated specimen experienced serious wear condition described by shearing and plastic distortion and the surface of the substrate has turned out to be rough and

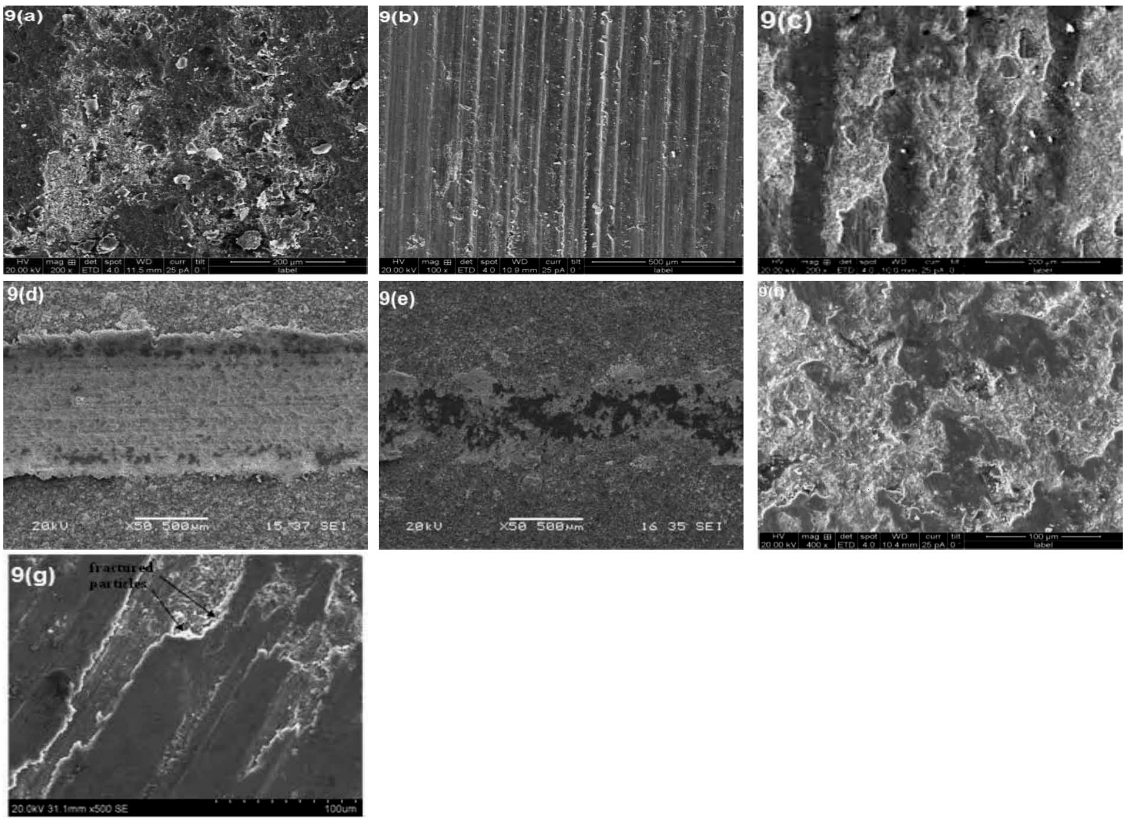

Figure 9: SEM microstructure after wear test of: a) Al_2O_3, b) TiO_2, c) Cr_2O_3, d) 45 Al_2O_3+55 TiO_2, e) 55 Al_2O_3 + 45 Cr_2O_3, f) 45 TiO_2 + 55 Cr_2O_3, g) AISI 1040 forged steel

debris formed because of the wear. The Al_2O_3-coated specimen had a wear mechanism on the surface in the form of flaky micro-cracks. This could be attributed to the high hardness values of the specimens. Micro-cracks occur if a critical value is exceeded in loading and abrasive wear also takes place in relation to the fracture toughness of the abraded material. The TiO_2-coated specimen showed that the wear mechanism on the surface formed micro-cutting of various widths along with plastic deformation because of micro crackings. **Figure 9g** reveals that the transfer of the materials that occurred from the pin to the disc. The debris produced throughout the test was deposited on both sides of the wear track. Over the wear track a few patches of the initial surface are observed, indicating that the transferred steel film was detached as a result of a fatigue process.

4 CONCLUSIONS

The AISI 1040 forged steel substrate was coated with alumina, titania, chromia individually and again with different combinations of ceramic oxides such as 45 % Al_2O_3 + 55 % TiO_2, 55 % Al_2O_3 + 45 % Cr_2O_3, and 45 % TiO_2 + 55 % Cr_2O_3 by using a plasma-spraying process with an intermediate bond coat of NiCr, SEM tests were carried out to determine the surface roughness and adhesion of the coating onto the AISI 1040 substrate.

The specimen coated with 99 % Cr_2O_3 has higher microhardness values among all the ceramic-oxide-coated specimens, which was followed by 99 % Al_2O_3, 45 % TiO_2 + 55 % Cr_2O_3, 55 % Al_2O_3 + 45 % Cr_2O_3. The lowest hardness value was obtained from the ceramic oxide coating surface with a mixture proportion of 45 % Al_2O_3 + 55 % TiO_2.

The chromia-coated specimen showed excellent wear property when compared to other coating materials due to its excellent adhesion to the base metal.

The increase in the weight percentage of TiO_2 in the Al_2O_3 ceramic material affects the microhardness value of the specimens in a decreasing manner.

The microhardness values of the coated specimens influence the wear loss. The specimens having higher microhardness also have a higher wear resistance and cause less wear loss.

If the weight percentage of TiO_2 in Cr_2O_3 ceramic materials increases, this decreases the microhardness value of the specimens.

From the experimental results it can be concluded that the pure 99 % Cr_2O_3 coated AISI 1040 forged steel specimen showed better wear resistance property due to dense, compact, defects free and good adhesion characteristics, while compared to other coating materials. Hence, it is recommended for surface coating on the top mill roll shafts used in sugarcane industries to increase the wear resistance of the shaft.

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