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Original

Tribological studies on bearings coated with titanium carbo-nitride (TiCN) using chemical vapour deposition (Cvd) method

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Abstract: The present work mainly focus on the development of a coating material for bearing applications using Chemical Vapour Deposition (CVD) method. The presence of coatings and surface topography play a vital role in the tribological performance of sliding components such as bearing. The coating used should reduce friction as well as wear of the components. An attempt has been made to develop a coating material that is provided on bearings in order to facilitate wear-resisting property improving the bearing properties significantly. Titanium Carbonitride TiCN is an extensively used material on tools used for abrasive cutting and machining operations, but still not used as a coating material in bearing applications. In this direction, (TiCN), an abrasion resistant ceramic coating was formed by adding a small amount of carbon to the Titanium Nitride (TiN) and the developed coating was applied on the bearings in the form of a thin film of 3 μm thickness. The carbon makes the coating harder and thereby provides a lower friction coefficient. Specimens were developed as per ASTM standards with size 10 x 10 x 20mm with and without coating material. The coated specimens were tested on Pin-on-disc wear testing machine and a comparative study between the TiCN coated bearing and the conventional bearing was carried out in terms of wear rates determination. SEM and EDAX analysis was also carried out for the tested specimens to ensure proper distribution of carbon in TiN. From the study it was found that the coated material showed lesser wear rate by 21% when compared to the conventional uncoated specimen and SEM showed proper bonding between the carbon and TiN.

Keywords: Tribology, Bearings, Titanium Carbo Nitride, chemical vapour deposition, wear rate

Abbreviations:

CVD: Chemical Vapour Deposition
TiCN: Titanium Carbo Nitride
SEM: Scanning Electron Microscope
EDX: Energy dispersive X-ray spectroscopy

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1. INTRODUCTION

Tribology is the science and engineering of interacting surfaces which are in relative motion and includes the study and application of the principles of friction, lubrication and wear (Hwang, Horng, Kao, Sawae, & Bartz, 2016). In automotive industry, normal wear and tear is expected to cause certain parts to wear out at a fairly predictable rate. One among these is bearings. By the end of the 20th century, development of effective bearings was carried out in order to reduce friction (Sivarajan, & Padmanabhan, 2015). A bearing is a machine element that constrains relative motion and reduces friction between moving parts to only the desired motion. There are different types of bearings such as ball bearing, roller bearing, thrust bearings etc. Bearings made from ceramics, chrome steels, stainless steels, are being used in large numbers. Unless properly and carefully designed and lubricated, these have a tendency to wear out. Historically, the first material used for making bearings was wood. The concept of bearings mainly involves two kinds of loading, radial and thrust. Depending on the application of bearing, it may be all thrust loading, all radial loading or combination of both. Hence the material used for bearings must be able to withstand such loads. The uncoated bearings used to wear out easily due to contact with the meeting surface so if there was an additional protective coating then wear rate and friction would be reduced by significant amount. Many structural and design methods have been developed which, to some extent, lessen or compensate for the tendency to wear. Bearings play a very vital role in automotive industrial applications as reported by Michigan Technic. It reduces friction between the moving parts in specified motion. It even supports axis of rotation in machinery. Most of today's bearings are made of bearing steel with the composition of carbon chromium steel (100Cr6), containing approximately 1% carbon and 1.5% chromium. Titanium is a metallic element having high strength to weight ratio (Freemantle, 2000). It has very high tensile strength even at high temperature, highly corrosion resistant and has high melting point of 1725°C making it a fairly good refractory metal as reported by (Ken Nduuku, 2016). Hence TiCN offers an excellent all-purpose coating material. TiCN is easily stripped and after getting five times the tool life with the original coating, that coating can be stripped and the part recoated, resulting in five times the tool life of the normal uncoated bearing as reported by the Panadyne tool manufacturer. Further it boosts the bearing life significantly as replacement of bearing itself is eliminated, thus reducing replacement cost. The TiCN coating improves the wear resistance of the bearing (Michigan, 1941). The present work focuses on development of a coating material consisting of TiCN and was subsequently applied as a thin layer on the bearings to enhance its properties and life as well.

2. NEED FOR COATING

After critically studying the present concept in the field of bearings and the wear related issues, it is reasonable to establish the need of an advanced coating like TiCN by CVD process. TiCN coatings have properties like higher melting temperature, elastic modulus, high wear resistance, good adhesion, low friction coefficient in relation to steel and high hardness and are widely deposited on the bearings to prolong the lifetime of the tools. There are many methods used to prepare TiCN coatings such as, Magnetron sputtering, CVD, Cathodic Arc Plasma deposition (CAPD) and other vapour deposition methods (Hedaiatmofidi et al., 2014). Each method has its advantages for specific application. Among them, CVD is a promising and effective technique (Sivarajan, & Padmanabhan, 2015).

As compared to other techniques CVD has series of advantages, e.g. the equipment of CVD is simple and is well suited for coatings as rate of deposition is rapid with optimum temperature and adhesion to substrate is quite good. In general, this increases smoothness and toughness of the bearing surface. Titanium nitride (TiN) coatings deposited by different physical vapor deposition (PVD) and chemical vapor deposition (CVD) techniques are now widely accepted in a range of industrial applications with high demands in wear resistance and adhesion to the substrate (Al-Jaroudi, Hentzell, Gong, & Bengston, 1991) of thin Solid Films (Wu et al., 1990). Surface morphology of the coating strongly affect the tribological performance of TiCxN1-x coatings besides influences of substrates, thickness of the coatings, deposition sequences (in multilayer or graded coatings) and the type of wear, also (Bull, Bhat, & Staia, 2003) . It has been also reported in the literature that limitations of CVD and PVD techniques can be overcome using Pulsed laser deposition technique (Major et al., 2004). PLD is one of the few coating techniques that fulfill the demands of both room-temperature depositions besides providing very smooth coating surfaces (Lackner, Waldhauser, Ebner, Keckés, & Schöberl, 2004a, 2004b). Effects of excimer laser annealing on low-temperature solution based indium-zinc-oxide thin film transistor fabrication (Chen, & Huang, 2015). In the present investigation, the development of TiCN coated bearings by CVD was adopted. Using of Pin on disc testing machine, the parameters such as wear rate, coefficient of friction of coated and uncoated bearing specimens were obtained and the results were analyzed.

3. EXPERIMENTAL ANALYSIS

This section discusses on the experimental strategy adopted in the study. CVD method was adopted for coating the novel developed material on bearings as it is suited best for hard coatings like oxides, carbides, nitrides. CVD technique can produce coatings with uniform thickness and low porosity even on complex-shaped substrates. In CVD technique, a coating of TiCN was done on the heated surface of the bearing steel via a chemical reaction from the vapour and the CVD set up used is shown in Figure 1.

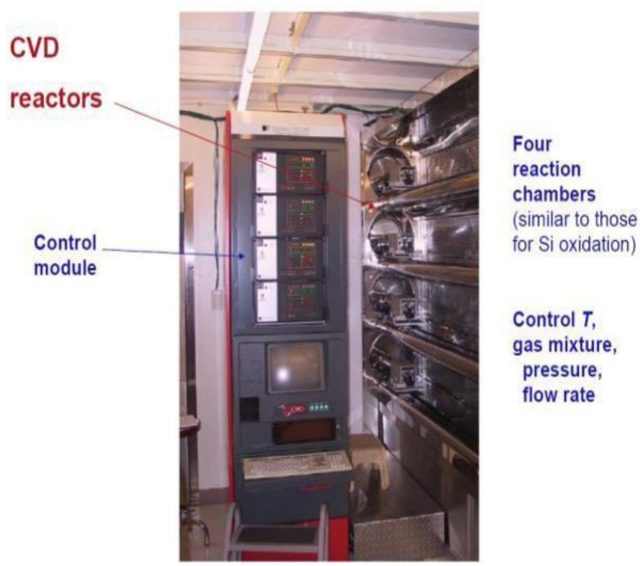


Fig. 1. CVD Setup.

During coating, process parameters such as gas flow rate, growth temperature, and total pressure etc were monitored. The flow rate of CH_4 was maintained at 0.5 to 3 liters per minute. The distance between activation heater and the substrate was maintained at 3.5 to 6.0 mm. Total pressure was kept at 20-50 Torr and substrate heater temperature was maintained between 1025 to 1050°C and activation heater temperature range was maintained 1250 to 1450°C. Deposition duration was kept between 30 to 120 minutes. The thickness of TiCN thin films were measured using AFM which revealed the thickness of the coated film as shown in Fig. 2.

Six specimens of coated and uncoated materials developed were tested as per ASTM standards and the averaged out readings are only used in the results and discussion section. Table 1 shows the properties of TiCN film coating provided on the bearing. The hardness of

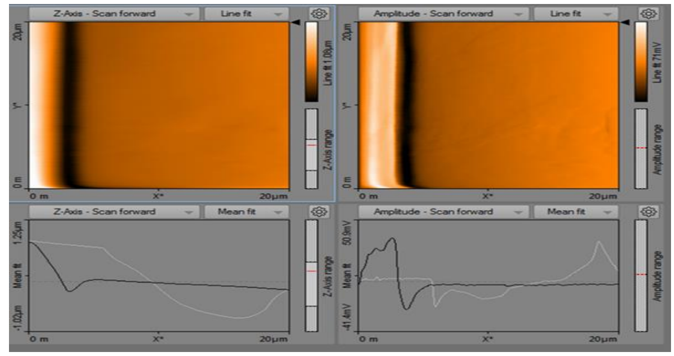


Fig. 2. Measurement of TiCN thin films using AFM.

bearing steel 15330 is shown in Table 1. Table 2 shows the properties of TiCN.

A layer of Ti was deposited, followed by nitrogen introduction to produce a layer of TiN after which C_2H_2 was introduced gradually to produce TiCN coating. The machine element to be coated is kept inside the closed chamber as shown in Figure 2. TiCN coating of 3µm thin film was provided on the bearing specimen.

3.1 DRY SLIDING WEAR BEHAVIOR

The dry sliding wear behavior of TiCN coated bearings are known to possess superior wear resistance when compared to that of the uncoated bearings. Hence these coated bearings were effective to be used in areas where severe wear and tear occurs during the usage. The bearings undergo adhesive wear which is strongly influenced by hardness of these materials. Both coated and uncoated specimens wear tested on pin-on-disc testing machine to determine the wear, coefficient of friction and the results were compared. Lower abrasive wear rates were found for TiN coatings without carbon while high friction coefficients were observed for these samples. These results were found to be in good agreement with those published in the literature (Martinez, Wiklund, Esteve, Montala, & Carreras, 2002).

Table 1. Properties of TiCN.

Material	H (Gpa)	E (Gpa)	H2/E2	We (%)
Steel 15530	9.9	890	0.00054	0.1

3.2 WEAR TEST:

Dry (unlubricated) sliding wear tests of the uncoated bearing and TiCN coated bearings were carried out at ambient temperature, using a pin-on-disc wear-testing machine (DUCOM, India) as shown in Figure 3 according to ASTM G99-05 standard. Table 3 shows the specifications of Pin on disc machine.

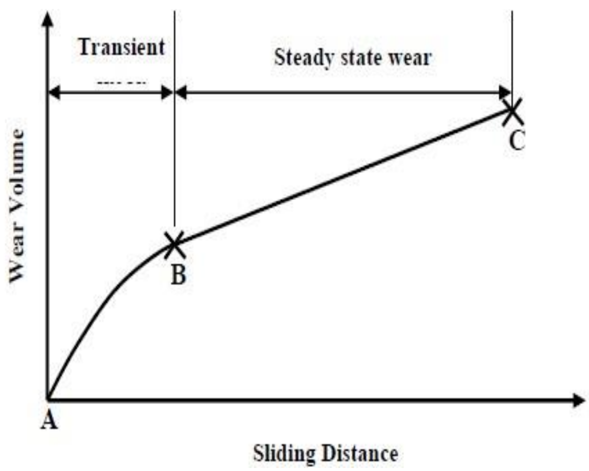


Fig. 3. Variation of Wear volume against sliding distance.

Table 2. Properties of TiCN.

Parameter	Property of TiCN
Friction coefficient	Low
Heat resistance	Low
Oxidation Temperature	400°C
Hardness	High
Color	Blue- grey
Nano - Hardness	37
Thickness [µm]	1-4
Friction-(fretting)	0.20
Maximum usage temperature	400

For this purpose, uncoated roller bearing specimen made of bearing steel was polished against 600-grade SiC paper to obtain specimens having a cross section of 10 x 10 x 20mm. A disc made of hardened chromium steel (EN-31, hardness 62 Rc) was used as the counter body against the pin. The specimen is held stationary and the disc is rotated while a normal force is applied through a lever mechanism. This acts as the counter face to wear against the composites coating. Prior to tests, both pin and disc were polished to have a uniform surface roughness. A computer aided data acquisition system was used to simultaneously record both height loss and frictional force, with the volumetric loss being calculated.

Table 3. Specifications of Pin on disc setup.

Test Parameter	Values
Specimen pin size	3 to 12 mm diameter in steps of 2mm,20 to 30mm long
Wear disc size	165x8mm
Wear track diameter	Min: 20rpm,max:100mm
Disc rotation	Min: 200rpm,max:2000rpm
Normal load	Min:5 N, Max:200N
Frictional force	Min:0N,Max:200N
Wear	2000 micrometer
Test ball dia	10mm

4. RESULTS AND DISCUSSIONS

This section provides results and discussion on the wear studies of the coated and uncoated bearing specimens.

4.1 WEAR PARAMETERS

Figure 3 shows a schematic plot of wear volume loss against the sliding distance, depicting the regions of transient and steady state sliding wear for a given sample. Initially the volume loss is curvilinear and the rate of volume loss per sliding distance decreases till point B, beyond which it is constant and follows a straight line BC. The amount of volume loss in the regime given by AB is the unsteady state or transient wear and the wear in the regime BC, is known as steady state wear. In the steady state wear regime, the wear volume loss occurs at a constant rate for an extended duration. The steady state wear behavior of materials is usually expressed in terms of certain wear parameters. The key parameters used in this study for quantifying the dry sliding wear behavior include the steady state wear rate, transient and steady state wear regimes.

Figure 4 shows the variation of volume loss as a function of sliding distance for both uncoated and coated samples. It may be noted that the rate of volume loss of uncoated specimen per sliding distance increase continuously thus attaining a steady state wear regime whereas in coated specimen the rate of volume loss is decreasing. The wear resistance, wear coefficient, specific wear rate and coefficient of friction were determined and are presented in Figures 5, 6, 7 and 8 respectively. Regardless of sliding velocity and sliding distance the wear rate of both the coated and uncoated samples increased with normal loads as shown in Figure 6. The reason being higher frictional thrust is obtained at increased load. With increase in carbon content of the coated specimen the material stiffness increases with decreasing deflection. The specific wear rate decreases with increase in applied normal load. It is observed that for higher loading conditions and increase in the sliding speed, the specific wear rate further decreases as shown in Figure 7.

4.2 COEFFICIENT OF FRICTION

Figure 7 and 8 shows the friction plot obtained from pin-on-disk test for both uncoated and coated bearing steel ball specimens. Manipulating the amount of different elements strongly influence the properties and behavior of the resulting coating on the bearing specimen. TiCN coating contains a surplus of carbon that has not reacted with the metal. TiCN coated samples has shown promising results with low friction and increased hardness and wear resistance. From the Figure 8 it follows that the friction starts at approximately 0.3 which is typical for an uncoated bearing against steel contact and then it increases to 0.65 which is typical for a selfmated bearing steel contact where as in the coated samples the friction starts at 0.4 initially and goes on decreasing to 0.2 as shown in figure 9. Initially the wear of the specimen is relatively large for coated specimen because in the beginning of the pin on-disk test the contact spot between the ball and the TiCN coated bearing is small and consequently the pressure is high.

During this running-in period the friction is decreasing and when the friction reach a steady state value the two surfaces in contact have been worn to fit each other irregularities perfectly, hence the contact pressure is much lower than at the start of the test. When this steady state has been reached the wear of the two surfaces is very small and the test can go on with low friction and wear for a long time. After the running-in there is almost no abrasion in the contact and the friction is hence mostly adhesive for the coated specimen as is evident in Figure 8. After the running-in a low steady-state friction coefficient was obtained. It is observed with increase in normal load at 1 m/s the coefficient of friction tends to increase. It can be noticed from the figure 8 that the co-efficient of friction of uncoated bearing sample has increased to a larger extent with increase in the normal load. While the coefficient of friction of coated (TiCN) sample has not increased to a large extent as compared to uncoated.

4.3 SEM (SCANNING ELECTRON MICROSCOPE)

The coated and uncoated bearings were examined using a scanning electron microscope (JEOL Model JSM - 6390LV, Tokyo, Japan) to view the surface and cross section views. For this the samples were vacuum dried initially. High resolution and magnification of surfaces of materials can be obtained by scanning electron microscope (SEM) while EDX provides detailed profiling of elements present on a particular surface.

Figures 9 and 10 shows the microscopic image of uncoated and coated bearing samples after the wear test was carried out respectively. From the figure 10 the abrasive scratches, cracks, pits and wear tracks on the bearing samples were clearly observable on the uncoated specimen when compared to the coated specimen. Coating material developed has provided a strong interfacial bonding between the components and the coated material as is evident from the SEM images as shown in Figure 11. Also the wear resistance offered by coated material is far superior to uncoated material as is evident in the discussion on wear results earlier. This is because the TiCN offers low porosity and dense structure.

4.4 ENERGY-DISPERSIVE X-RAY SPECTROSCOPY (EDX)

EDX is an analytical technique used for the elemental analysis or chemical characterization of a given sample (Al-Jaroudi et al., 1991). Energy Dispersive X-ray analysis was carried out on the coated surface of bearing steel to find the composition of the elements present in it. Figure 11 shows the Energy-dispersive X-ray spectroscopy (EDX) for both coated and uncoated samples. From the figure it is found that the coated TiCN film contains 83.63 weight% of titanium and 16.37 weight% of carbon. Nitrogen is comparatively in negligible amount. The high Titanium content present in the bearing steel provides higher wear resistance and low friction coefficient and the carbon content present further leads to corrosion resistance and excellent wear characteristics.

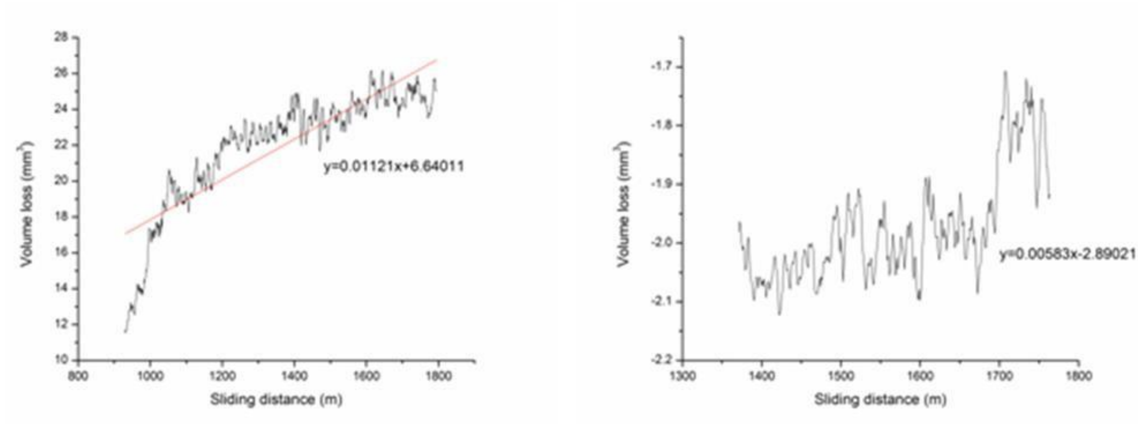


Fig. 4. Variation of volume loss v/s sliding distance of (a) uncoated and (b) coated sample.

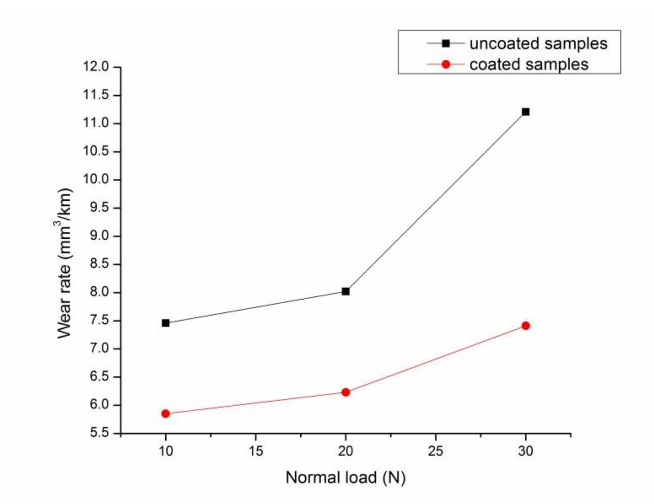


Fig. 5. Variation of wear rate (mm^3/N-km) vs normal load (N).

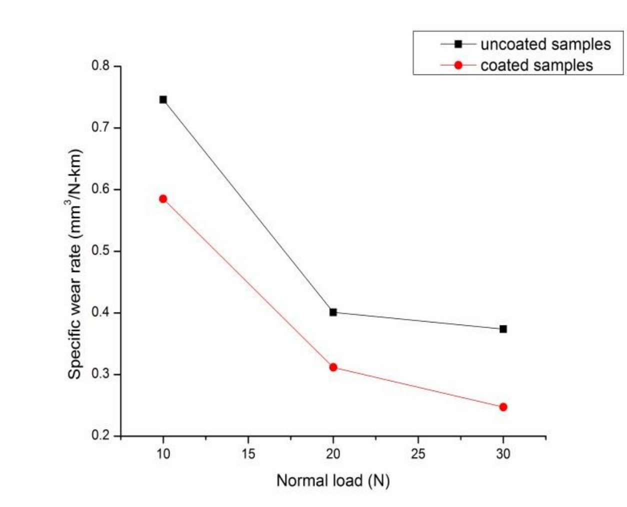


Fig. 6. Variation of specific wear rate (mm^3/N-km) vs normal load (N).

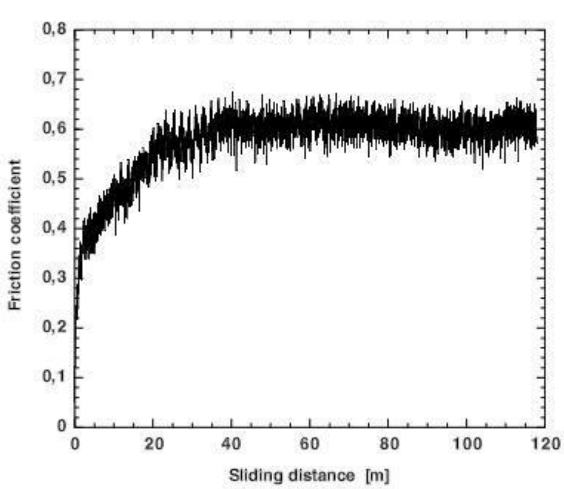


Fig. 7. Friction plot from pin-on-disk test of bearing steel ball against uncoated bearing.

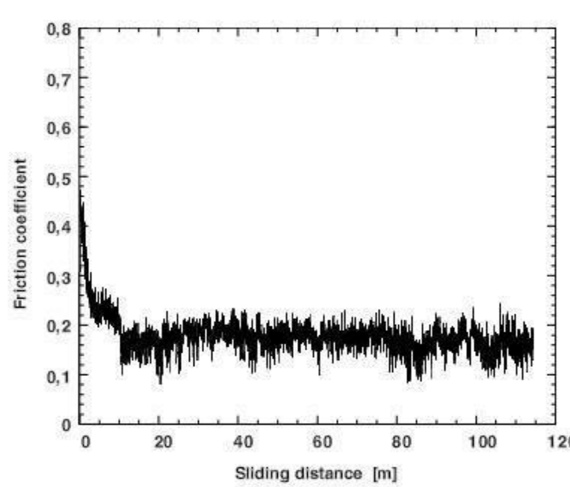


Fig. 8. Friction plot from pin-on-disk test of bearing steel ball against TiCN coating.

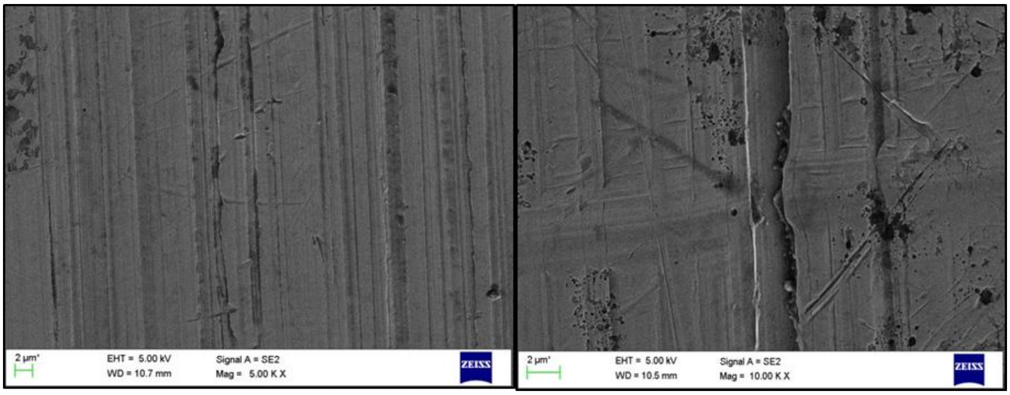


Fig. 9. SEM images of uncoated samples.

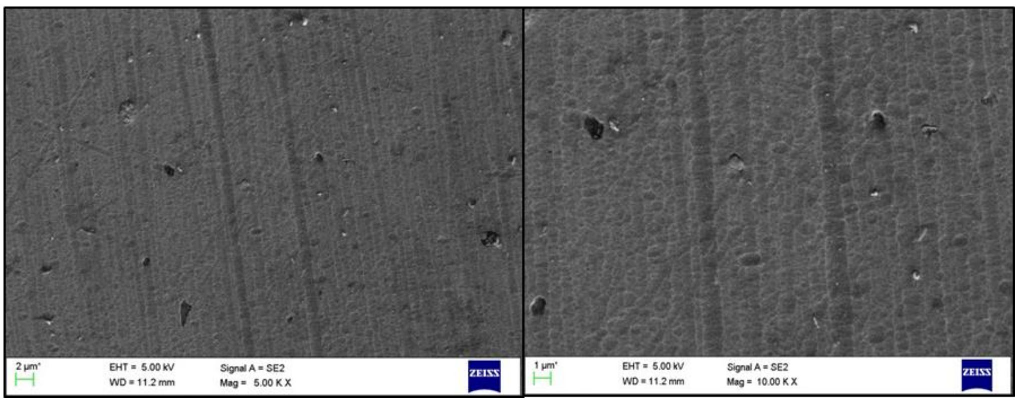
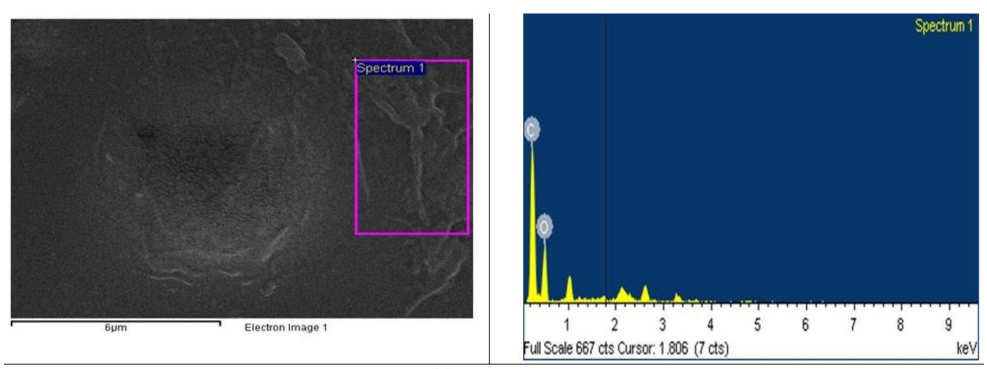
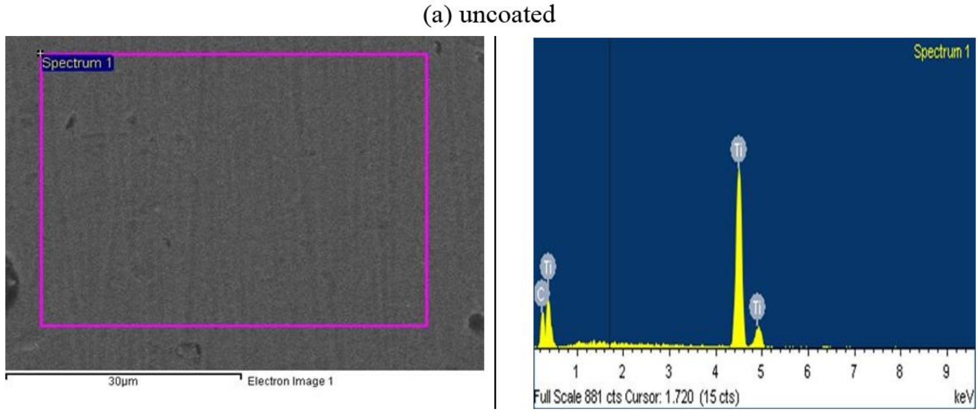


Fig. 10. SEM images of coated samples.



(a) uncoated



(b) coated

Fig. 11. Energy – dispersive X-ray spectroscopy (EDX).

5. CONCLUSION

Detailed experimentation was carried out to study comparative analysis of uncoated and coated bearing steel specimens for automotive applications. Based on the results obtained TiCN coated bearing samples showed promising results in terms of lowered friction, and higher wear resistance as well. From the wear test results, SEM images and EDAX images it is found that TiCN coated bearings has a very good co-efficient of friction, lower wear loss and higher wear resistance. Hence TiCN coated bearings can be used in automobiles because of their distinctive properties resulting in a longer life of bearings usage.

Recommendation for future research

A profilometric analysis can be carried out for the properties of the worn out surfaces.

CONFLICT OF INTEREST

The authors have no conflicts of interest to declare.

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