Tribological Properties of Coated and Uncoated Materials for Piston Ring Applications

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Abstract. Coating is an essential method to improve surface properties such as corrosion resistance, lubrication of material used. The simulated laboratory tests is a more feasible alternative to experimental or real-time testing. A study conducted under controlled parameters of load, surface coating, and temperature showed the changes in the tribological characteristics with and without functionally graded cermet coatings and their influence on stainless-steel piston rings. Altogether simulations for six cycles were taken into consideration for each of the test cases – with and without coating. The obtained data from the microstructure imaging in optical microscope following the investigation conducted employing tribometer showed that the resistance of the coated rings was comparatively more than the uncoated rings, hence proving the coating to be beneficial for real-time use.

Keywords: Frictional losses; Functionally-graded cermet coating; Microstructure Analysis; Plasma Spray Coating; Wear Resistance.

1. Introduction

The tribological characteristics of piston rings have been under investigation for decades concerning internal combustion engines. It is a well-known fact that there are frictional losses inside the cylinder of the engine over a while. Piston ring materials play an essential role and are in continuous contact with the cylinder liner. Piston rings act as a seal inside the cylinder to prevent the passage of combustion gases towards the crankshaft that would otherwise reduce the efficiency of the engine. For this very reason, piston rings must be of materials that show high corrosion resistance, wear, and friction resistance. With the advancement in science and technology, research, as well as the development of various ways to improve the tribological behavior of the piston rings and cylinder liners, is in progress such that they provide a hard-outer structure along with a soft inner-structure for withstanding the wear and absorbing the energy respectively. Coating is a useful technique to prevent these factors even though there have been previous attempts to replace stainless-steel pistons with aluminum pistons. Researchers have been conducting investigations and experimental studies to bring about changes in the material of the pistons such that they have favorable tribological characteristics for real-time uses. For this purpose, Kenny M, Hoppe, et al. developed new piston ring coatings [1]. Shanhong Wan et al. [2] studied the effects on the scuffing resistant capacity due to the integration of traditional ceramic coatings and their load-carrying capacity. Zheng Ma et al. [3] are well known for studying the tribological irregularities not only in piston rings but also in cylinder liners. Ronghua Wei et al. [4] are well-known for the assessment of nanocomposite coatings characterized by improved mechanical strength, increased life of performance as well as decreased rates of friction for piston rings. M. Palanivendhan et al. [5] conducted an experimental evaluation of composite coatings of an aluminum alloy whose properties showed improvement by using silicon carbide for use in the automobile sector. Hyo-Syo et al. [6] investigated the tribological properties of composite coatings that had the presence of Al2O3, TiO2, ZrO2 employing plasma spray technique. Huadong et al. [7] proposed that cast iron having low phosphorous content when closely compared with a matching Al2O3 – 40% ZrO2 coating applied to employ plasma spray coating in the presence of lubricated conditions showed better resistance with high and low phosphorous content than with the medium amount of phosphorous.
Tribological characteristics, specifically ceramic coatings applied using plasma spray technique was investigated by Giovanni Bolelli et al. [8] and compared with the microstructure properties of more commonly used ceramic coatings. Experimental studies were carried out by Sun Yong [9] to understand the effect of SMA treatment on the wear in stainless-steel of grade AISI 304 both with and without lubrication. The theory that composite coatings are known to have increased the resistance to wear due to high temperatures were analyzed by Subba Rao Medabalimi et al. [10] during the investigation conducted on the effects of NiCr coating containing Al in a partially oxidized form. The characteristics of piston ring functioning and the challenges faced during their operations due to irregularities in tribological properties and manufacturing defects were studied and summarized by Rita Ferreria et al. [11]. Wenping Li et al. [12] compared the influence of four different types of coatings for piston rings namely - Physical Vapor Deposition Coating, Chromium, Goetze Diamond Coating, and Plasma Chemical Vapor Deposition Coating. They concluded that GDC or Goetze Diamond Coating showed the least wear rate while Chromium showed the highest. Marcus Kennedy et al. [13] developed a special coating for piston rings used in high-charged gasoline engines. This coating was named Carbodlidge and was known to reduce losses incurred due to friction and wear. Swain et al. [14] studied the mechanical properties of NiTi smart alloy coatings when applied to mild-steel by atmospheric plasma-spray technique. Hwang et al. [15] subjected piston ring specimens to high temperatures and studied the wear characteristics of these specimens when coated using the plasma spray technique. The wear properties of pistons ring. The crux of these experiments was to understand the wear and friction of piston rings under various tribological conditions. Based on these works, an investigation was carried out to understand the influence of functionally-graded cermet coating on stainless-steel piston rings.

2. Materials and methods

2.1 Materials used

The piston uses stainless-steel as the substrate, which provides corrosion resistance, cryogenic toughness, and higher ductility, strength, and hardness. But it wears off due to continuous usage. A ceramic coating of 60% Al2O3 + 40% TiO2 applied through the plasma spray coating method ensures less wear. The ceramic compounds used as heat-resisting barriers because of low conductivity along with other factors like the high coefficient of thermal expansion that brings about less wear in the substrate. The properties of this coating and its easy availability make it a suitable choice for conducting this particular experimental study.

2.2 Plasma Spray Coating Procedure

Plasma spray coating is a technique of applying heated and ionized material on the surface of a substrate by injecting the powder form of the coating material into a high-temperature plasma plume. The material heated to a high temperature of nearly 16000o K makes this a feasible option for applying a coating of uniform thickness. The material is accelerated through the nozzle at a high velocity onto the substrate while maintaining a fixed temperature. When the hot coating material comes within proximity of the substrate, heat transferred from the hot particle to the cold surface causes the particle to shrink and solidify. The plasma spray gun is composed of an anode and a cathode. The presence of gases like He, H2, or N2 is necessary between the anode and the cathode. A high voltage discharge initiates the plasma spray causing ionization. That created a path for a DC arc between the anode and the cathode. The heat generated from the arc forms a plasma, and the gas dissociates and ionizes due to extreme temperatures. The powder sprayed can reach a 25 to 150mm distance. Plasma spray coating provides the benefit of high corrosion and wears resistance and conductivity. Based on these advantages, the composition of the functionally-graded cermet coating was 60% Al2O3 + 40% TiO2. The thickness of the ceramic coating obtained employing this procedure was 350 µm. The thickness of the bonding material zirconium oxide (ZrO2) was 150 µm.

Figure 1 shows the virtual representation of the plasma spray coating technique.
2.3 Ceramic Coating Characteristics

The ceramic coating applied on the stainless-steel piston rings consists of 60% Al2O3-Alumina and 40% TiO2-Titania in powder form. Due to the presence of high hardness and strength determined by strong ionic bonds in Al2O3, alumina has a considerable amount of resistance to different types of wear and is one of the components for the functionally graded cermet coating. It is well-known that high wear resistance and hardness brings about substrate corrosion and thermal protection. The addition of Al2O3 increases the bonding strength without bringing about any changes to the ductility. Properties like wear resistance, coefficient of friction, and fracture toughness in Al2O3 show improvement with the use of TiO2. The addition of TiO2 leads to the formation of a dense and hard ceramic coating as it is chemically inert and provides protection against a significant decrease in ductility or embrittlement. TiO2 is known to enhance protection against wear by hard surfaces when combined with Al2O3. The combination of Alumina and Titania has a melting point of 3340 F that served the purpose of high wear-resistant and high-quality finishing. The properties of Alumina-Titania ceramic coating such as high dielectric strength, resistance to heat up to 1000 F make it a viable option for reducing wear and friction in stainless-steel piston rings. Resistance to wetting and corrosion by aqueous and dilute alkali solutions bring about a very smooth finish with high bond strength. Based on the previously mentioned properties, the coating is composed of 60% Al2O3 + 40% TiO2. For the bond coating, 150 microns of ZrO2 was used, which provides a protective layer owing to the presence of high thermal, mechanical, and electrical characteristics. Zirconium, being lighter than steel, has high thermal stability. This property makes it fit for being used in ceramic coatings at high temperatures. The quoted and unquoted specimen are shown in the figure 2(a) and 2(b).

2.4 Pin-on-disc test

Tribometers are instruments or devices used for the tribological investigation of the materials. One of the most common tribometers used is the pin-on-disc setup, a high-frequency reciprocating machine. A dry-testing method was employed to ensure easy installation and cleaning purposes. The pin installed in the fixture holder resembled the material of the piston ring, and the rotating disc resembles a section of the cylinder liner. For this particular experimental investigation, the material used for the disc is EN31, high carbon steel known for its hardenability. The pin of 25mm length, and diameter, 9mm, was used. Under a constant load of 40N, the pin is pressed against the rotating disc of diameter 60 mm. The disc rotates at the speed of 400 rpm for 1 hour. The test was for six cycles, each cycle having a duration of 1 hour. The heater block present in the setup consists of a piezoelectric transducer that measures the frictional force occurring between the pin and the disc.
Different discs were used for each cycle, while the same pin was used by cleaning it ultrasonically before and after each cycle. The graphs from the previously mentioned process gave the wear rate, and the frictional force encountered. Table 1 shows the details of the equipment used. The original setup of the apparatus is in Figure 3 and the schematic diagram in Figure 4.

![Figure.3 Pin-on-disc setup](image)

**Table 1. Equipment details**

| Wear and Friction Monitor     | (Pin on Disc Monitor)                |
|-------------------------------|--------------------------------------|
| ASTM Standard                 | G99                                  |
| Wear Disc diameter            | Diameter - 100mm & Thick - 6 to 8mm  |
| Pin diameter                  | 4 - 8mm diameter in steps of 2mm     |
| Length                        | 20 - 30mm length                     |
| Frictional Force              | Max 100 N                            |
| Wear                          | 0 - 2000 microns                     |

![Figure.4 Schematic representation of pin-on-disc setup](image)

2.5 Microstructure Analysis
The microstructural analysis process evaluates the microstructure in a metal alloy. The observation made shows the crystal analysis and possible metal deformations in the specimen after the pin-on-disc test. The
wear encountered was observed at 100x magnification after every cycle. The microstructure analysis paves a path for a better understanding of the irregularities observed in the tribological characteristics during the pin-on-disc test.

3. Results and discussion

3.1 Pin-on-disc setup readings and observation

The data obtained were analyzed for changes in the wear rate and the frictional force. The pin was ultrasonically-cleaned before and after performing the test. The graphs plotted for the frictional force and the wear rate against the data points showing the results obtained.

3.2 Observation of frictional force

From the graphs given below, it is visible that after using the same specimen for six cycles of lab testing each of 1 hour, the amount of frictional force on both the uncoated and coated specimen increased from Cycle 1 to Cycle 6. When the data obtained were compared, it was evident that, although the amount of frictional force increased from Cycle 1 to Cycle 6 individually for both the coated and uncoated specimen, the frictional force in the case of the coated specimen was comparatively less than that of the uncoated specimen. Even that the highest mean value of frictional force, the uncoated specimen had a value of 27.1, as seen in Figure 5.11, while the coated specimen had a value of 16.7 in Figure 5.12. The same was the case at the lowest values. The uncoated specimen had a mean frictional value of 13.6, shown in Figure 5.1, whereas the coated specimen had a value of 12.9, evident from Figure 5.2.

![Figure 5.1 Uncoated – Friction](image1)

![Figure 5.2 Coated – Friction](image2)

![Figure 5.3 Uncoated – Friction](image3)

![Figure 5.4 Coated – Friction](image4)
Figure 5.5 Uncoated – Friction

Figure 5.6 Coated – Friction

Cycle 4

Figure 5.7 Uncoated – Friction

Figure 5.8 – Coated – Friction

Cycle 5

Figure 5.9 Uncoated – Friction

Figure 5.10 Coated – Friction

Cycle 6

Figure 5.11- Uncoated – Friction

Figure 5.12 Coated – Friction
3.3 Observation of wear encountered

Corresponding to the amount of friction between the pin and the disc, both for the uncoated and coated specimen, the amount of wear observed from the graphs plotted between wear encountered against the data points shows that the value of wear shows a continuous increase and after one stage, it tends to become constant. The only exception to the previously stated point is the graphs obtained from Cycle 1. There is an uneven increase in the wear rate, which is visible through the microstructure imaging. This happens due to sudden application of load on the specimen without any previous contact with any other surfaces. The mean value of wear in the uncoated specimen, after cycle 6, is found to be 1585 from Figure 5.23, and in Cycle 1 is 374 from Figure 5.13, respectively. For the coated specimen, the mean value of wear in the coated specimen in Cycle 6 is 1341, evident from Figure 5.24, whereas in Cycle 1 is 111, as seen in Figure 5.14.

As the testing process progresses from Cycle 1 to Cycle 6, the value of both the uncoated specimen and the coated specimen increase individually due to continuous application of pressure, but at the highest and the lowest values of the wear, the amount of wear in the coated specimen is comparatively less than that of the uncoated specimen.

![Figure 5.13 Uncoated – Wear](image1)

![Figure 5.14 Coated – Wear](image2)

![Figure 5.15 Uncoated – Wear](image3)

![Figure 5.16 Coated – Wear](image4)

![Figure 5.17 Uncoated – Wear](image5)

![Figure 5.18 Coated – Wear](image6)
3.4 Microstructure Imaging and Analysis

A microstructure analysis performed using an optical microscope just before and after each cycle for both the coated and uncoated specimen. The lab test showed the presence of voids and visible cracks in the uncoated material as well as the coated material. However, the irregularities observed in the uncoated specimen were higher as compared to the coated specimen due to the defects resulting from the fabrication processes. In the uncoated specimen, due to setbacks like stainless steel, it is observed to be susceptible to easy scratching off of material due to wear and friction or easy scuffing as seen in Figure 6.1, 6.3, and 6.5 during cycles 1, 3 and 6, respectively. The irregularities found during the 1st cycle causing large portions of uneven wear larger in number as compared to be more than the aberrations noticed during the 6th cycle. In the case of the coated specimen, cracks can also be the result of the high range impact on the specimen during the plasma spray coating or the high temperatures used for applying the powdered-coating. This results in excessive thermal stresses, which are not visible to the naked eye, but with the help of an optical microscope. Another reason for these cracks can be the sudden uneven solidification of the bonding material zirconium oxide (ZrO2) and the ceramic coating (60% Al2O3 + 40% TiO2). It leads to the formation of uneven layers of the coating that haven’t blended well into each other, thereby causing uneven wear at some places but, when compared to uncoated specimens, they are less. Uneven layers are visible in the microstructure imaging of the 1st cycle for the coated specimen, which reduces further in the 6th cycle owning to the value of wear becoming constant after the continuous increase. However, the appearance of
these irregularities seems to be less in the case of the coated specimen when compared to the uncoated specimen, indicating that the zirconium-based functionally graded Alumina-Titania cermet coating provides better resistance to both wears as well as friction. Therefore, the reduction of the amount of wear that would take place in an ordinary stainless-steel piston ring specimen in real-time cases as seen in Figures 6.2, 6.4, and 6.6 during cycles 1, 3 and 6 respectively.

4. Conclusion
From the results of the tests performed on coated and uncoated piston rings, it can be concluded that the resistance of the coated piston ring was found to more than the uncoated aluminum piston by 14.5%. The resistance of the piston was found to more than the uncoated steel piston by 11.3%. The frictional force as well as the wear increased starting from Cycle 1 to Cycle 6 each of a duration of 1
hour. This was evident both in the case of uncoated and coated specimen. Although the values of frictional force and the wear increased over a period of time, the amount of wear in the coated specimen was less than the uncoated specimen even during the 6th Cycle. The microstructure images obtained, showed aberrations like, voids and visible cracks both in uncoated and coated specimens. However, these aberrations were less in the coated material as compared to the uncoated material. From the results obtained, the graphs plotted and the microstructure imaging, it is evident that the coated piston rings yield comparatively less wear with the uncoated piston as a result of a reduced amount of friction during the movement of the piston rings against the cylinder lines in real-time usage.

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