Final Draft
of the original manuscript:

Srinivasan, P.B.; Liang, J.; Blawert, C.; Dietzel, W.:

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In: Applied Surface Science (2009) Elsevier

DOI: 10.1016/j.apsusc.2009.12.017

Dry sliding wear behaviour of magnesium oxide and zirconium oxide plasma electrolytic oxidation coated magnesium alloy

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Keywords

Magnesium alloy; plasma electrolytic oxidation; microstructure; dry sliding wear.

Abstract

Two types of PEO coatings, one consisting of magnesium oxide (MgO) and the other comprising zirconium oxide (ZrO₂) as the main phase composition were produced on AM50 magnesium alloy from alkaline and acidic electrolytes, respectively. The ZrO₂ coating was found to be spongy and thicker with a higher roughness, whilst the relatively more compact MgO coating was having contrasting features. In the dry sliding oscillating wear tests under two different loads viz., 2N and 5N, the ZrO₂ coating exhibited a very poor wear resistance. The MgO coating showed an excellent resistance to sliding wear under 2N load; however, the load bearing capacity of the coating was found to be insufficient to resist the wear damage under 5N load. The higher specific wear rates of the MgO coating under 5N load and that of the ZrO₂ coating under 2N and 5N loads were attributed to the poor load bearing capacity and a three-body-abrasive wear mechanism.

Introduction

Owing to their light weight, good castability, recyclability and reasonably good mechanical properties, magnesium alloys are an attraction to the automobile and electronic industrial sectors. For meeting the application demands, the components made of magnesium alloys need to be given suitable surface treatments to provide the aesthetic appeal, corrosion resistance and tribological properties [1]. Even though a wide variety of surface modification technologies viz., electro and electroless plating, vapour deposition, conversion coatings, organic coatings etc., are available [2-6], plasma electrolytic oxidation (PEO) has been one among the most preferred treatments for magnesium alloys, as the ceramic oxide coating formed by PEO processing offers an excellent corrosion resistance and wear resistance, as well [7-8]. Corrosion behaviour of a variety of PEO coatings have been studied by many researchers [9-11]. The authors' group has recently studied the corrosion and stress corrosion cracking behaviour of PEO coated magnesium alloys [12-14].

Even though the microstructure-corrosion behaviour correlation has extensively been reported by researchers, the published information on the tribological behaviour of PEO coated magnesium alloys is very limited. The abrasive wear behaviour of PEO coated magnesium alloy was reported by Goretta et al. [15].

The adhesive dry sliding wear behaviour of the PEO coated AM60 magnesium alloy against Si_3N_4 ball was reported by Liang et al. [16] and the adhesive wear behaviour of a silicate based PEO coated AM50 magnesium alloy has been reported recently [17]. As there are only a handful of publications on the zirconium oxide (ZrO_2) based PEO coatings on magnesium alloys [18-19], recently the authors produced a ZrO_2 coating from an acidic zirconate solution for magnesium alloys, and compared its electrochemical behaviour with that of the magnesium oxide based PEO coating obtained from an alkaline phosphate electrolyte [20]. As the ZrO_2 coatings have been found to be promising from the context of long term corrosion resistance in chloride environment, it was decided to assess the tribological behaviour of the two coatings and understand the suitability of these coatings for applications involving dry sliding conditions.

Experimental

Coupons of size 40 mm × 40 mm × 4 mm from an AM50 magnesium alloy (mass fraction: 4.4 to 5.5% Al, 0.26 to 0.6% Mn, max 0.22% Zn, max 0.1% Si, and Mg balance) were used as the substrate in this investigation. The specimens were ground successively with different grit emery sheets viz., 500, 1200 and 2500, before the PEO treatment.

The plasma electrolytic oxidation processes were carried out using a pulsed DC power source with a frequency of 50 Hz in alkaline phosphate and acidic fluozirconate electrolytes, respectively. During the PEO process, the magnesium alloy sample and the wall of the stainless steel container were used as the anode and cathode, respectively. The alkaline phosphate electrolyte contained Na_3PO_4 (8 g/l) and NH_4OH (18 g/l) in distilled water. The formation of the oxide coatings was achieved at a constant current density (30 mA/cm^2) for 10 minutes. The fluozirconate electrolyte was constituted with K_2ZrF_6 (3.0 g/l) and NaH_2PO_2 (1.0 g/l) in distilled water. To get the PEO coating on magnesium alloy in the acidic fluozirconate electrolyte, a primary flash coating was prepared firstly in the alkaline phosphate electrolyte to inhibit anodic dissolution of the magnesium alloy in the acidic solution at the initial stage of processing. As it was difficult to keep the constant current density in the fluozirconate electrolyte during the PEO process, the PEO process was performed at a constant voltage of 420 V for 10 min. The temperature of both PEO electrolytes was maintained at $23 \pm 2^\circ\text{C}$ with the use of a cooling system. All coated samples were rinsed thoroughly in water and dried in air after the PEO process.

The surface roughness of the coatings was assessed using a Hommel profilometer, and thickness of the coating was determined using MiniTest 2100 meter. X-ray diffraction (XRD) was performed using a Philips PW1820 diffractometer with $\text{Cu-K}\alpha$ radiation to determine the phase composition of the PEO coatings. Scanning electron microscopy was used to examine the surface morphology of the PEO coatings which were sputtered with a thin gold film in order to prevent surface charging effects.

The dry sliding wear behaviour of the untreated and PEO coated specimens was assessed using a Tribotec ball-on-disc oscillating tribometer with an AISI 52100 steel ball of 6 mm diameter as static friction partner. The wear tests were performed at ambient conditions ($22 \pm 2^\circ\text{C}$) under 2N and 5N loads with an oscillating amplitude of 10 mm and at a sliding velocity of 5 mm s^{-1} , for a sliding distance of 50 m. Wear depth measurements were performed with the Hommel

profilometer. The worn balls and the wear tracks were examined and characterized in a Zeiss Ultra 55 scanning electron microscope equipped with energy dispersive X-ray spectrophotometer.

Results and Discussion

Phase composition and microstructure

X-ray diffraction (XRD) analyses performed to assess the chemical composition of the PEO coatings revealed that the coating produced in the alkaline phosphate electrolyte was mainly composed of MgO (**Figure 1(a)**). Interestingly, no chemical compounds associated with the main anion in the electrolyte viz., phosphate, were detected in the coating. Instead, only a broad peak was seen in the XRD pattern in the range $2\theta = 20^\circ$ to 30° , which suggests the plausible existence of phosphate in amorphous form in the coating. In the case of the PEO coating produced from acidic fluozirconate electrolyte, characteristic peaks of tetragonal ZrO_2 (*t*- ZrO_2) and monoclinic ZrO_2 (*m*- ZrO_2) phases were predominant (**Figure 1(b)**). In addition, a few peaks corresponding to MgF_2 and MgO were also observed. These results indicate that fluozirconate from the electrolyte participated in the plasma-thermo-chemical reactions during the PEO process and were incorporated into the coating as zirconium oxide. In both PEO coated specimens the diffraction peaks of Mg corresponding to the substrate were seen, which is due to the fact that the tests were performed at incident X-Ray conditions and not in low-glazing angle mode. Based on the main phase composition of the PEO coatings identified in XRD, the alkaline phosphate and acidic fluozirconate coatings are addressed as “MgO” and “ ZrO_2 ” coatings, respectively, in the following discussions.

The surface and cross-section morphologies of the MgO and ZrO_2 coatings are shown in **Figures 2 (a) – (d)**. The morphology of the MgO coating presented in Figure 2(a) reveals a surface with numerous pores of different sizes. The mean surface roughness (R_a) of the MgO coating was $2.2 \pm 0.2 \mu\text{m}$. The ZrO_2 coating shown in Figure 2(c) had a different surface appearance compared to the MgO coating. Two distinct characteristic regions were identified on the surface. One was the so-called sintered protrusions with relatively large-sized micropores (region X in Figure 2(c)), and the other was the surface with numerous smaller micropores (region Y in Figure 2(c)). Due to the above morphological features, the surface of the ZrO_2 coating was very rough which was confirmed by the roughness measurements ($R_a = 3.6 \pm 0.6 \mu\text{m}$).

The cross-section morphology of the MgO coating shown in Figure 2(b) reveals that the major part of the coating was relatively compact, even though some defects were observed in the inner regions of the coating. In the cross-section of the MgO coating spherical pores were observed, some of which were filled with coating compounds, and a few others were like gas bubbles. The thickness of the MgO coating was $28 \pm 5 \mu\text{m}$. The globular shaped pores filled with the coating compounds and the hair-line crack features of a sectioned portion of an inter-connecting pore are marked as (i) and (ii), respectively, in this micrograph. On the other hand, the thickness of the ZrO_2 coating was $40 \pm 8 \mu\text{m}$ (Figure 2(d)) and unlike the case of the MgO coating, the cross-section of the ZrO_2 coating contained relatively large irregular-shaped pores and micro-cracks which are marked as regions (i) and (ii), respectively, in Figure 2(d). In addition, a few circular and irregular-shaped pores of different sizes were also observed in this coating. A closer examination of the ZrO_2 coating further revealed that it was having a sponge-like structure.

Wear behaviour

Figure 3 shows the variation in the friction co-efficient during the 50 m sliding in the oscillating wear tests of the sliding couple consisting of uncoated and PEO coated magnesium substrate plates and an AISI 52100 steel ball under a load of 2 N. A friction co-efficient value in the range of 0.28 – 0.32 was registered when the untreated magnesium alloy was slid against the steel ball. Much higher friction co-efficient values were registered during sliding of MgO and ZrO₂ coated magnesium alloy specimens against the steel ball. In the case of the MgO coated specimen, the friction co-efficient value was observed to rise in the first 15 m of sliding to reach a steady-state value of 0.73 ± 0.02 . In the case of the ZrO₂ coated specimen, the friction co-efficient value rose instantly to around 0.70. The value increased further to reach a steady-state value of 0.82 ± 0.02 during 5 m and 40 m of sliding. After this point, a few sharp fluctuations were observed. Nevertheless, the value remained above 0.70 until the test was terminated after 50 m of sliding. To the best of the knowledge of the authors, there is no published work on the tribological behaviour of ZrO₂ coated (through PEO) magnesium alloys. However, Jun et al., have observed a friction co-efficient value in the range of 0.60 – 0.70 for the PEO coating which was constituted predominantly with MgO when slid against a Si₃N₄ ceramic ball [21]. The same group reported a friction co-efficient value in the range of 0.70 – 0.80 for silicate PEO coated magnesium alloy slid against Si₃N₄ ball [22]. In a recent work on silicate based PEO coated AZ91 alloy a slightly higher steady-state friction co-efficient value was reported from sliding wear tests against an AISI 52100 steel ball under 2N load [23].

The scanning electron macrographs of wear tracks of the untreated AM50, MgO and ZrO₂ coated magnesium alloy specimens slid against a steel ball under a load of 2N load are shown in **Figures 4 (a) – (c)**, respectively and the wear track depth profiles of the respective specimens are shown in **Figure 4(d)**. The wear track on the untreated magnesium specimen was found to have deep scoring marks in the direction of sliding, and the surface was covered with wear debris (Figure 4(a)). Whilst the coating in the wear track of the MgO coated specimen appears to be intact (Figure 4(b)), the coating in the wear track of ZrO₂ coated specimen seems to have been removed completely during the wear test under 2N load (Figure 4(c)). The above observations were supported by the wear depth measurements. Also, a few patches of magnesium substrate underneath the surface covered with wear debris could be seen in the above macrograph.

The width and depth of the wear track of the untreated magnesium alloy were found to be around 1040 μm and 35 μm , respectively, which accounted for a specific wear rate of $1.8 \times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ for the alloy. Even though the depth of the wear track in the case of the untreated specimen could easily be measured from the distinct depth profile, it was difficult to precisely measure the depth in the wear track of MgO coated specimen. However, the specific wear rate of the MgO coated magnesium alloy was calculated to be around $2.4 \times 10^{-4} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, assuming a depth of 6 μm from the highest valley in the wear profile. This value may even be an overestimate, but still it was lower than the untreated alloy by an order of magnitude. It is interesting that the wear rate of the ZrO₂ coated specimen was higher than that of even the untreated specimen. The wear depth was found to be around 80 μm in this specimen. The width of the wear track as measured by profilometer showed a higher value than the value that was measured from the scanning electron micrograph of wear track (Figure 4(c)). As can be noticed from the micrograph, the coating had crumbled along the edges of the wear track, and also had formed some ridges in these regions. Hence, for the

wear rate calculations the wear track width was taken as an average of profilometry data, wear track SEM and also from the contact area of the worn ball surface. The specific wear rate of the ZrO_2 coated specimen under 2N load was found to be $5.0 \times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$. It was reported that the wear resistance of the PEO coating obtained from phosphate electrolyte was inferior to the coatings produced in a silicate based electrolyte [21]. In this work, amongst the two coatings produced, viz., MgO and ZrO_2 , the former one produced from the phosphate electrolyte was found to exhibit a superior wear resistance on account its better compactness, as can be observed in Figure 2b. Even though the earlier work [21] showed a higher thickness coating could provide a superior load bearing capacity and offer a better wear resistance, the thicker ZrO_2 coating seems not to have offered the expected wear resistance essentially on account of the porous and spongy structure, which is evident in Figure 2d.

The scanning electron macrographs of the surfaces of the corresponding counterpart (steel ball) surfaces are shown in Figures 5(a) – (c). The steel ball which slid against the untreated magnesium alloy did not show any signs of wear damage. The contact region marked in circle in Figure 5(a) shows the surface covered with transferred wear debris from the magnesium alloy. The degradation and removal of material as a result of sliding appears to have started as abrasive wear owing to the large hardness differences between the hard AISI 52100 steel ball (~900 HV) and the soft magnesium substrate (80 HV), as is evident from the deep scoring marks in the wear track. It is plausible that the hard secondary β -phase ($\text{Mg}_{17}\text{Al}_{12}$) and the Al_8Mn_5 particles removed from the substrate could have also participated in the wear process, causing the damage. Even though the surface of the steel ball did not undergo any visible wear damage, due to the adhesive wear mechanism that prevailed at the interface after the initial abrasive wear, transfer of debris from the magnesium substrate to the steel ball had resulted, which can be seen in Figure 5(a).

In the case of the steel ball slid against the MgO coated magnesium alloy, an abrasive wear of the ball was observed. The hardness of both PEO coated substrates (MgO and ZrO_2) was not measured. However, it has been reported that the PEO coatings on magnesium alloys have hardness values in the range 400 – 600 HV. It is interesting that the steel ball with a hardness of around 900 HV suffered an abrasive wear damage against the MgO coated surface (Figure 5(b)). The wear rate of the steel ball was found to be $6.8 \times 10^{-5} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, and the flattened worn surface steel ball contained scoring marks. A few isolated wear debris seen as dark particles on the steel ball appears to have come from the initially levelled out MgO layer from the coated surface. As mentioned earlier, there was only a very little wear damage to the MgO coated magnesium alloy surface. On contrary, the surface of the steel ball slid against the ZrO_2 coated magnesium alloy did not undergo any wear damage (Figure 5(c)). The original spherical shape of the ball at the contact surface was seen intact, as was observed in the case of the ball slid against the untreated magnesium alloy. However, some wear debris could be observed on this surface, which has apparently got transferred from the ZrO_2 coated surface.

A higher magnification scanning electron micrograph from the wear track of the untreated magnesium alloy substrate tested under 2N load is shown in Figure 6(a). Deep scoring marks, fragmented and agglomerated debris can be seen in this micrograph. In the energy dispersive spectroscopy (EDS) analyses performed on this region of the wear track, characteristic peaks of high intensities corresponding

to Mg and O were observed, suggesting the oxidation of magnesium surface during the wear process. This in turn indicates that the wear debris seen on the steel ball could not only comprise the adhesively transferred magnesium but the oxide debris as well. There was no trace of iron in the EDS spectra, which reaffirms the fact that there was no wear of the steel ball in this case. The higher magnification micrograph from the wear track of MgO coated surface and the corresponding EDS spectrum are shown in **Figures 6(b) and (c)**. The micrograph clearly reveals that the exterior layer of the coating in some regions has slightly been damaged but the whole of the underneath coating remained intact (regions marked by arrow). In some regions the presence of loose debris is evident, and in some regions the MgO coating appeared to have been pressed onto the surface. Characteristic high intensity peaks of Mg, O, Fe and P seen in the EDS spectra clearly illustrate the wear of the steel ball, and the possible formation of iron oxide. It is believed that the loose debris seen on the surface is constituted with both magnesium oxide and iron oxide and some fine iron particles as well. The worn surface micrograph from the wear track of ZrO₂ coated specimen and the corresponding EDS spectrum are shown in **Figures 6(d) and (e)**, respectively. The high intensity characteristic peaks of Mg, F, Zr and O indicate remains of the compounds of ZrO₂ and MgF₂ on the surface. As it was clearly seen from the profilometry studies on the wear track that the ZrO₂ coating was completely damaged, it is believed that the appearance of Zr and F peaks in the wear track is on account of the fine wear debris seen smeared on this surface.

In the wear tests performed under 2N load, the MgO coating provided an excellent resistance under dry sliding conditions. Nevertheless, a small but perceptible abrasive wear damage was inflicted on the steel ball. The better wear resistance is attributed to the good compactness of the MgO coating. On the other hand, the internal structure with large sized pores and inter-connecting micropores makes the ZrO₂ coating less compact, and the loosely bound compound mixture of this thick ZrO₂ coating could not resist the load under conditions of dry sliding. Not only that the coating was completely removed, but the debris generated through the wear process further caused a three-body abrasive wear damage to the soft magnesium substrate, and thus resulted in a higher specific wear rate of the ZrO₂ coated magnesium alloy. The wear depth profile in the case of ZrO₂ coating tested under both 2N and 5N loads showed removal of substantial amounts of magnesium from the substrate underneath the coating, which is attributed to the three-body abrasive wear that prevailed upon during the test. It should be pointed out that the friction co-efficient value remained high throughout the sliding period in this case, and this indicates that the steel ball was in contact only with the fragmented/removed compounds of the ZrO₂ coating. The slight fluctuations at the end of the test suggest the metal-to-metal contact between the steel ball and magnesium substrate at those isolated patches marked by arrows in Figure 6(d).

The sliding wear behaviour of the magnesium substrate-steel couple was evaluated at 5 N load, and the corresponding friction coefficient plots are presented in **Figure 7**. The wear behaviour of the untreated magnesium substrate under 5N load was similar to that observed under 2N load. The friction co-efficient value remained around 0.30 throughout the 50 m sliding test. The friction co-efficient value of the MgO-steel couple rose to around 0.70 in a shorter time compared to that observed in the 2N test, and dropped to around 0.40 after about 3 m of sliding. Thereafter, the value fluctuated between 0.30 and 0.40 for the rest of the sliding distance. In the case of the couple involving ZrO₂ coated magnesium substrate, the friction co-efficient value rose to around 0.80 rapidly similar to the

2N case, and started to drop slowly and steadily after about 5 m of sliding. The value remained in the range 0.40 – 0.50 after about 15 m of sliding until the end of the test.

The scanning electron macrographs of the wear tracks of the untreated and PEO coated magnesium alloy substrate after 50 m of sliding under 5 N are shown in **Figures 8(a) – (c)**. The presence of deep scoring marks with fine wear debris was seen in the untreated specimen, whilst in the wear track of ZrO₂ coated surface the magnesium alloy substrate was exposed with the complete removal of coating. However, the surface was still covered in a few places with patches of smeared loose wear debris. These features are similar to those observed in the 2N test for the respective specimens. On the other hand, the 5 N wear track on the MgO coated specimen was completely different from that obtained under 2 N. The MgO coating seems to have been completely removed, and this is corroborated by the friction co-efficient data. The specific wear rates of the untreated, MgO and ZrO₂ coated specimens were 1.4×10^{-3} , 2.3×10^{-3} and $5.1 \times 10^{-3} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$, respectively. The specific wear rate of the untreated specimen was slightly less under 5 N when compared to that under 2 N. It is probable that the deformation and the work hardening of the magnesium substrate would have caused this. The specific wear rate of the MgO coated specimen was significantly higher under 5 N load. The point stress under this load at the initial stages of sliding had seemingly damaged/crumbled the 30 μm thick MgO coating and thus had resulted in a higher wear rate. Surprisingly, the specific wear rates of the ZrO₂ coated specimens tested under 5 N and 2N loads were nearly the same. This could be attributed to the fact that in both cases the coating was completely removed and the wear debris from the coating played the further role of inflicting a three-body abrasive wear on the magnesium substrate. It was found in a work on the wear behaviour of silicate PEO coatings on a magnesium alloy that a 10 μm thick coating failed in the wear tests under a load of 5 N, whilst a coating with around 20 μm thickness could resist wear even under a load of 10 N without any signs of noticeable wear damage [23]. The above information and the observations of the current work reaffirms the fact that the load bearing capacity of the coating is instrumental in dictating the wear under high stresses experienced at the initial stages of the sliding, and defective/less compact coatings are prone to greater damage.

The scanning electron macrographs of the steel ball surfaces slid against the untreated, MgO coated and ZrO₂ coated specimens under 5N load are shown in **Figures 9(a), (b) and (c)**, respectively. In all the three cases the ball did not undergo any wear damage and only the transfer of material/debris from the magnesium substrate could be observed. The higher magnification micrograph from the untreated magnesium alloy wear tracks presented in **Figure 10(a)** reveals the scoring marks and also the fragmented wear debris. In the EDS analysis major elemental peaks of Mg and O were observed, suggesting that the surface had oxidised and the fragmented debris could be magnesium and/or magnesium oxide. In the wear tested MgO coated specimen surface (**Figure 10(b)**), debris of very fine size compared to the earlier case was noticed. In the EDS spectrum (**Figure 10(c)**) characteristic high intensity peaks of Mg, O and Al were observed. Similarly the higher magnification wear track micrograph shown in **Figure 10(d)** reveals scoring marks and fine wear debris and the EDS spectrum (**Figures 10(e)**) from this track showed characteristic peaks of Mg, O, Al and traces of F. Thus, it is evident from the above EDS spectra that both PEO coatings were completely removed when slid against the steel ball for a distance of 50 m under dry sliding conditions under 5 N. Even though the MgO and ZrO₂ coatings produced in this

work were much thicker compared to the silicate coating thickness reported in the earlier cited work [23], but still, both these coatings failed completely under 5 N load. This clearly illustrates that the wear resistance and load bearing capacity of the coating is not only dependent on the thickness, but the intrinsic hardness of the coating, the degree of compactness and the defect levels in the coating collectively influence the performance. Even though the hardness values of the MgO and ZrO₂ coatings could not be measured in this work, the other two aspects viz., compactness and defect levels, have been well demonstrated by the microstructural evaluation and correlated effectively to the dry sliding wear behaviour.

Conclusions

PEO coatings comprising MgO and ZrO₂ as the main phase composition can be produced from alkaline and acidic electrolytes, respectively. Even though the ZrO₂ coating had a higher thickness, it gets deposited as non-dense and spongy structure with numerous fine pores and cracks. Even though the MgO coating with a thickness of around 30 µm can resist dry sliding wear under 2 N load, it could not survive the wear test under 5 N on account of poor load bearing capacity. The three body abrasive wear that gets set-up by the entrapment of wear debris in the sliding couples involving the PEO coated specimens led to higher specific wear rates of the coated alloy than the untreated substrate. The ZrO₂ coating obtained in this work was found to enhance the wear damage, and hence may not be suitable for tribological applications involving dry sliding conditions.

Acknowledgements

P. Bala Srinivasan and J. Liang express their sincere thanks to the Hermann-von-Helmholtz Association, Germany and DAAD, Germany for the award of fellowship and funding. The technical support of Mr. V. Heitmann, Mr. U. Burmester and Mr. V. Kree during the course of this work is gratefully acknowledged. The authors thank Dr. Zhiguang Guo, Laboratory of Inorganic Materials Chemistry (CMI), University of Namur (FUNDP), Belgium, for the XRD analysis.

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Figure 1 X-ray diffraction patterns of the (a) MgO and (b) ZrO₂ coated magnesium alloy

Figure 2 Scanning electron micrographs of the PEO coated specimens (a) & (b) MgO coating, (c) & (d) ZrO₂ coating.

Figure 3 Friction co-efficient data from the dry sliding wear tests involving untreated and PEO coated AM50 magnesium alloy under 2N load

Figure 4 Scanning electron macrographs showing the wear tracks in the untreated and PEO coated specimens tested under 2N load (a) untreated, (b) MgO coated, (c) ZrO₂ coated, (d) wear depth profile

Figure 5 Scanning electron macrographs showing the appearance of worn ball surfaces slid against (a) untreated magnesium alloy, (b) MgO coated alloy, (c) ZrO₂ coated alloy under 2N.

Figure 6 Higher magnification scanning electron micrographs of the wear tracks (tested under 2N) and their corresponding EDS spectra (a) untreated, (b-c) MgO coated, (d-e) ZrO₂ coated

Figure 7 Friction co-efficient data from the dry sliding wear tests involving untreated and PEO coated AM50 magnesium alloy under 5N load

Figure 8 Scanning electron macrographs showing the wear tracks in the untreated and PEO coated specimens tested under 5N load (a) untreated (b) MgO coated (c) ZrO₂ coated

Figure 9 Scanning electron macrographs showing the appearance of worn ball surfaces slid against (a) untreated magnesium alloy (b) MgO coated alloy, (c) ZrO₂ coated alloy under 5N

Figure 10 Higher magnification scanning electron micrographs of the wear tracks (tested under 5N) and their corresponding EDS spectra (a) untreated (b-c) MgO coated (d-e) ZrO₂ coated