The effect of different metallic counterface materials and different surface treatments on the wear and friction of polyamide 66 and its composite in rolling-sliding contact

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Abstract

*The effect of different metallic counterface materials and different surface treatments on the tribological behaviour of polymer and polymer composite under unlubricated, non-conformal and rolling-sliding contact has been investigated. The most widely used polymer materials - unreinforced polyamide 66 and its composite (RFL4036) – were tested. The metallic materials include aluminium, brass and steel and the surface treatments include Tufftride** treated (known as nitrocarbonising) and magnesium phosphate treated, etc. Tests were conducted over a range of slip ratios at a fixed load of 300 N, 1000 rpm rotational speed using a twin-disc test rig. The experimental results showed that the polyamide composite exhibited less friction and wear than the unreinforced polyamide 66 when running against steel and aluminium counterfaces. However, when tested against brass, polyamide 66 exhibited lower wear than the composite. The surface treatment of steel has a significant effect on the coefficient of friction and the wear rate, as well as on the tribological mechanism, of polyamide 66 composites. It has been observed that a thin film on the contact surface plays a dominant role in reducing the wear and friction of the composite and in suppressing the transverse cracks. This study clearly indicates that both the characteristics of the different counterface metallic materials and the surface treatment greatly control the wear behaviour of polyamide 66 and its composite.*

Keywords: Wear, Polyamide 66 composite, metals and surface treatments, Rolling-sliding contact

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** ***Tufftride*** is a heat treatment process and many British companies, such as TTI Group Ltd, provide this process.

1. Introduction

Components made from injection-moulded Polyamide 66 (PA66) and PA66 composites running in non-conformal rolling-sliding contact are widely used in engineering. Typical examples include gears, cams and rolling element bearings. PA66 has been reported to have superior wear resistance to other polymers due to its ability to form a thin and uniform transfer film while sliding against steel counterparts [1-7]. Clerico et al [8] reported that there were no substantial differences in the wear rate of particle filled PA66 running against bronze and glass-fibre reinforced PA66 composite running against steel when in rolling-sliding contact. It has also been shown that the transfer of film from the polymer to the steel counterface reduces both the friction and the wear rate due to a change in the sliding conditions from polymer sliding on metal to that of polymer sliding on polymer [9]. The friction and the wear behaviour of the polymeric material depends on the nature, thickness and stability of the transfer film that is formed and on the properties of the metallic counterface material [9]. However, relatively little research has been carried out when both PA66 and PA66 composite (RFL4036) run against different grades of steel with different surface treatments as well as different counterface materials in non-conformal rolling-sliding contact [5-14].

The results reported here, are part of a study aiming to select a metallic mating material for PA66-based gears. The investigation is concerned with the effect of three different metallic counterface materials (aluminium alloy 2011, BS2874 brass and EN24 steel) on the wear and friction of unreinforced PA66 and PA66 composite. The effect of the surface treatments of mating steel, Tufftride treated and magnesium phosphate treated, on the wear and friction behaviour of RFL4036 is also investigated. Details of the composition and surface hardness of the materials used in the study are listed in Table 1.

Table 1 Materials and dimensions of tested discs

Materials	**Composition**	**Surface Hardness**	**Dimensions** (mm)
R1000	Polyamide 66 (PA66)		30 in diameter 10 in facewidth
RFL4036	PA66, 15wt%PTFE, 30wt% short glass fibre		
Brass BS2874 (CZ121-Pb4)	58%Cu, 38%Zn and 4%Pb	121H_V	
Aluminium (2011)	5-6%Cu, 0.7%Fe, 0.3%Zn, 0.2-0.6%Pb, 0.2-0.6%Bi, 0.4%Si	113H_V	
EN24 Steel	0.36-0.44%C, 0.1-0.35%Si, 0.45-0.7%Mn, 1.0-1.4%Cr, 1.3-1.7%Ni and 0.2-0.3% Mo	683H_V	
EN08 Steel	0.36-0.44%C, 0.10-0.40%Si, 0.60-1.00%Mn, 0.05%S and 0.05%P	245H_V	

2. Experimental details

The twin-disc wear testing machine used in our previous work [12-14] was employed in this investigation. Two discs were arranged in contact with one above the other. The lower disc was mounted in a rigid block while the upper disc was supported in a pivoted block and loaded downwards by a deadweight load. Friction was measured by noting the horizontal force on the lower block and a continuous measurement of the movement of the upper block enabled the wear process to be monitored throughout the tests. The discs were driven by an electric motor via a power transmission system linked by universal joints, with different speeds between the two discs being obtained from a gear pair in the power transmission system. Wear was also measured by weighing the discs before and after a test. Experiments were carried out either at different slip ratios under a given normal load or at different loads with a given slip ratio. With this method the typical loading and sliding conditions of engineering components in non-conformal, rolling-sliding contact can be simulated [13-14].

The materials used were supplied by LNP Ltd and were polyamide 66 (R1000) and short-glass fibre reinforced PA66 with PTFE (RFL4036) [11]. The proportions of glass fibre added was 30 wt% and PTFE was 15 wt%. To ensure proper contact along the facewidth of the discs all of the specimens were prepared by machining 20 μm from the moulded surface and then polishing to a surface roughness of around 5 μm. Both discs were 30 mm in diameter and 10 mm in facewidth.

Before testing, the disc samples were cleaned with methanol. They were then run at the test conditions for an extended period to bed-in the surfaces and to remove the machining asperities and any subsurface layer affected by the manufacturing process. After bedding-in they were dried at 70^{o}C for 15 hours to remove any absorbed water that might affect the measurement of wear and then weighed. Finally, they were left under atmospheric conditions for about two weeks to allow the water content to return to equilibrium conditions. After this preliminary treatment the specimens were remounted in the test rig in an identical position to that under which they had been run-in.

Tests were run for a running speed of 1000 rpm (the rotational speed of the lower disc [12-14]) and at a load of 300 N and slip ratios. Slip ratio is defined here as the ratio of sliding to rolling velocities. If the tangential velocities on both contact surfaces are v_1 and v_2 respectively then the sliding velocity is (v_1-v_2) and the rolling velocity is (v_1+v_2)/2. The slip ratios used were between 0 and 0.29. Tests were operated under dry, unlubricated conditions at ambient temperature $(22\pm1)^{o}$C until failure or for up to 10^6 contact cycles.

At the end of the test the discs were again dried at the same temperature and for the same time period as those before they were tested. Then, the discs were weighed to measure the weight loss of each disc. Using this drying procedure the measurement of wear by weighing is accurate to about $\pm 1\text{x}10^{-4}$g. Finally, the worn surfaces were observed in detail by using a Scanning Electron Microscope.

3. Experimental results

Fig.1 presents the amount of wear of the different mating disc pairs as a function of contact cycles. It is evident that the amount of wear increases with the number of contact cycles. A typical wear versus number of cycles plot may consist of up to three stages. The first stage shows an apparent negative wear right at the beginning of each test as a result of thermal expansion of the specimens. During the second stage some discs ran smoothly against each other undergoing very little if any wear. In some cases a third stage was observed where catastrophic wear took place. However, some samples suffered catastrophic wear, without going through the intermediate smooth stage. The results of these observations are summarised in Table 2.

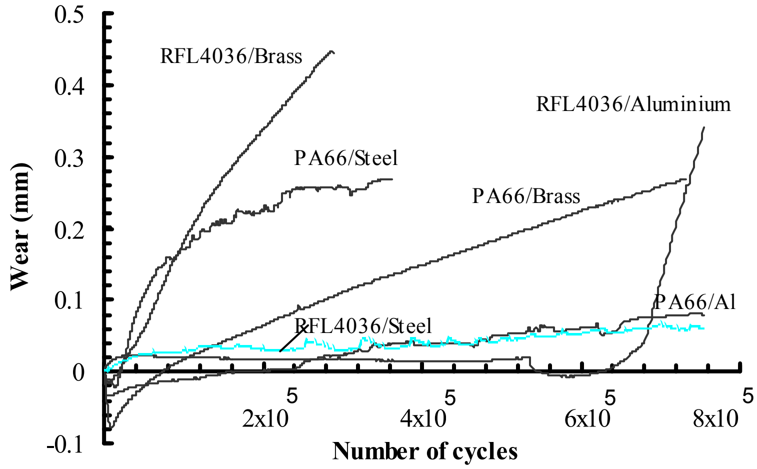


Fig.1 Wear of different mating disc pairs versus test duration running at 300 N, 1000 rpm, and 0.29 slip ratio.

Table 2 Wear stages observed during testing

SAMPLE COMBINATION	WEAR STAGES OBSERVED
PA66/EN24	1, 3
PA66/BS2874 brass	1, 3
PA66/2011	1, 2
RFL4036/EN24	1, 2
RFL4036/ BS2874 brass	1, 3
RFL4036/2011	1, 2, 3

Note: 1 = negative wear at beginning of test
2 = smooth stage showing little or no wear
3 = catastrophic wear

The PA66/brass pair suffered a fast wear rate without showing an intermediate smooth stage. The wear rate remained almost constant for the whole of the test cycle. The wear rate for the PA66/steel sample was even higher initially, but it declined significantly with time as a result of the gradual formation of a visible PA66 layer on the steel surface. The PA66/2011 combination suffered the lowest wear for all the samples involving unreinforced PA66. Wear protection was provided by the formation of visible PA66 transfer film on the surface of the aluminium alloy. The RFL4036/brass pair underwent catastrophic failure right from the start of the test. In contrast the RFL4036/aluminium sample experienced a long intermediate stage of low wear followed by catastrophic wear after 6.5 x 10^5 cycles. The lowest wear for the composite material took place when running against EN24 steel.

The composite RFL4036 exhibited lower wear than the unreinforced PA66 when the tests were run against the EN24 steel counterface discs. The highest wear for RFL4036 was observed when brass was the counterface material. The RFL4036/2011 combination suffered the lowest wear for about 6.5×10^5 cycles, whereupon it suddenly started to wear catastrophically. It was observed during the test that the catastrophic wear was associated with the break-up of the transfer film which had been formed on the contact surface of 2011 during the period of the first 6.5×10^5 cycles. It was also noted that the wear of PA66 was the highest when it was tested against steel, while when tested against 2011 it was the lowest.

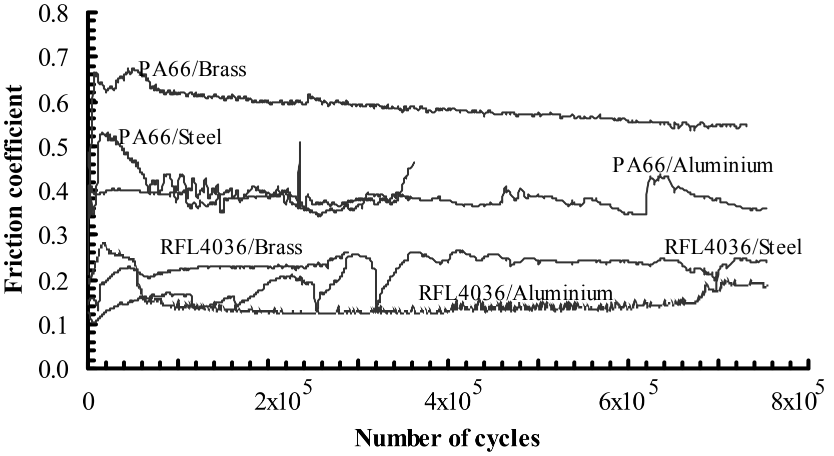


Fig.2 Friction coefficient of different mating disc pairs versus test duration running at 300N, 1000 rpm, and 0.29 slip ratio.

The friction coefficient of different mating disc pairs against the number of test cycles is shown in Fig.2. The friction coefficient was observed to increase rapidly at the beginning of each test, followed by practically no variation for samples where the transfer film remained intact. RFL4036 composite experienced a lower friction coefficient than the unreinforced PA66 irrespective of the metallic counterface materials used as shown in Fig.2. The reason for this is probably due to the presence in the polymer of about 15wt% PTFE that has a low friction coefficient. The value of the coefficient of friction for both PA66 and RFL4036 was observed to be at its highest when running against brass and at its lowest with 2011, while with EN24 steel an intermediate rise in friction coefficient was observed.

Fig.3 shows the wear rate of the individual materials under different mating combinations. It is apparent that the metallic counterface materials suffer very little if any wear when sliding against PA66. When in contact with RFL4036, EN24 steel showed an insignificant amount of wear. The worst of the metallic performers was the brass. A comparison of the results obtained when running PA66 and RFL4036 against 2011 shows that RFL4036 wears much more than the PA66. The surface of 2011 and RFL4036 had shown a tendency to fuse together thereby damaging the protective transfer film. RFL4036 was observed to wear at a higher wear rate than PA66 when the tests were run against brass. It is also noted that PA66 wears out at a higher rate than RFL4036 when the steel disc was used as the counterface material. Overall, the RFL4036-brass pair experienced the highest wear rate, whereas the RFL4036-steel combination was observed to have the lowest wear rate amongst all mating combinations studied.

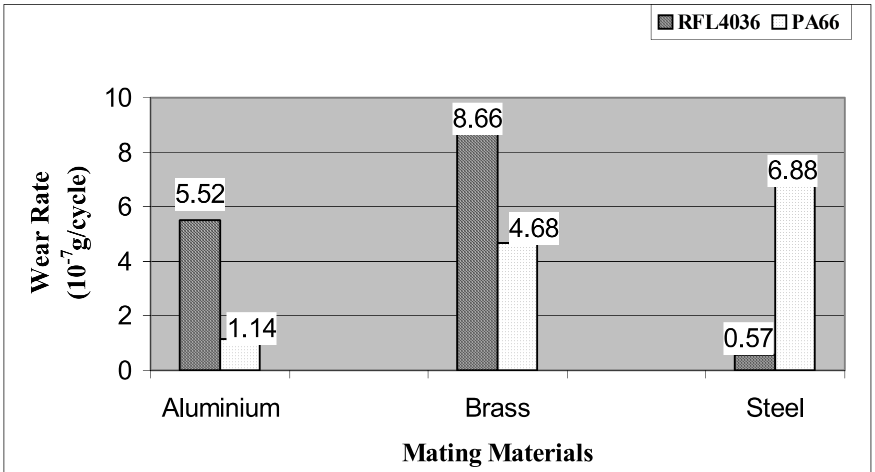


Fig.3 Wear rate of PA66 and RFL4036 versus counterface materails running at 300N, 1000rpm, and 0.29 slip ratio.

Figs.3-4 show the wear rates of RFL4036 running against different grades of untreated steel, EN24 and EN08. The wear rate of RFL4036 was 5.7×10^{-8} g/cycle when running against EN24 steel and was 14.8×10^{-8} g/cycle when running with EN08 steel. The difference between them is about 3 fold.

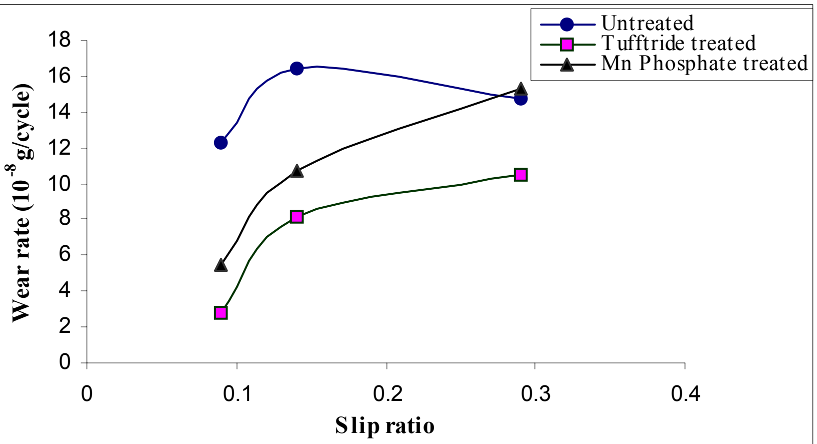


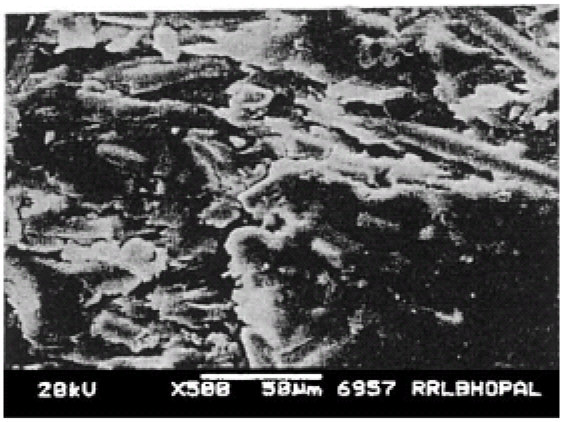
Fig.4 Wear rate of RFL4036 running against steel (EN08) with different surface treatments at 300N and 1000rpm.

The effect of both the surface treatments of the mating steel (EN08) and the slip ratio on the wear rate of RFL4036 are presented in Fig.4. The wear rate of RFL4036 running against Tufftride coated steel takes lowest value of all three different surface treatments, Tufftride coated, manganese phosphate coated and untreated steel. The wear rate increases sharply from a slip ratio of 0.07 to 0.14. Then it only increases marginally with further increase of the slip ratio. The wear rate of RFL4036 running against manganese phosphate coated steel shows a similar trend to that of running against the Tufftride coated steel. However, the wear rate of RFL4036 running against untreated steel differs from the other two combinations by taking its highest value at a slip ratio of 0.14 rather than 0.29. This combination also has lower values of the wear rate at the other slip ratios. At a slip ratio of 0.29, the wear rates of RFL4036 running against manganese phosphate coated steel and untreated steel are very close, but they are much higher than that of RFL4036 running against the Tufftride coated steel.

4. Discussion

4.1 Characteristics of topography of the worn surface

Fig.5 shows the worn surfaces of RFL4036 when it was tested against three different mating materials. Figs.5a)-5b) show that the RFL4036 worn surfaces against both steel and aluminium become very smooth and that a thin layer of film appears on both of the worn surfaces. It can be seen that the film on the RFL4036 surface running against steel has been disrupted locally and part of film has been ploughed away from the surface. The RFL4036 worn surface running against aluminium shows the film maintaining its integrity. By contrast, Fig.5c) shows a completely different worn surface feature of RFL4036 against brass. A large amount of debris still remains on the worn surface, as shown in Fig.5c), even although a high amount of debris was expelled from the contact surface of the discs during the test. The brass debris was visibly recognisable compared with RFL4036 debris.



(a)

(b)

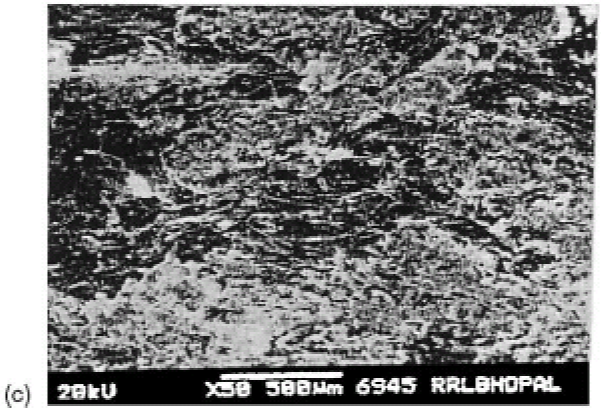
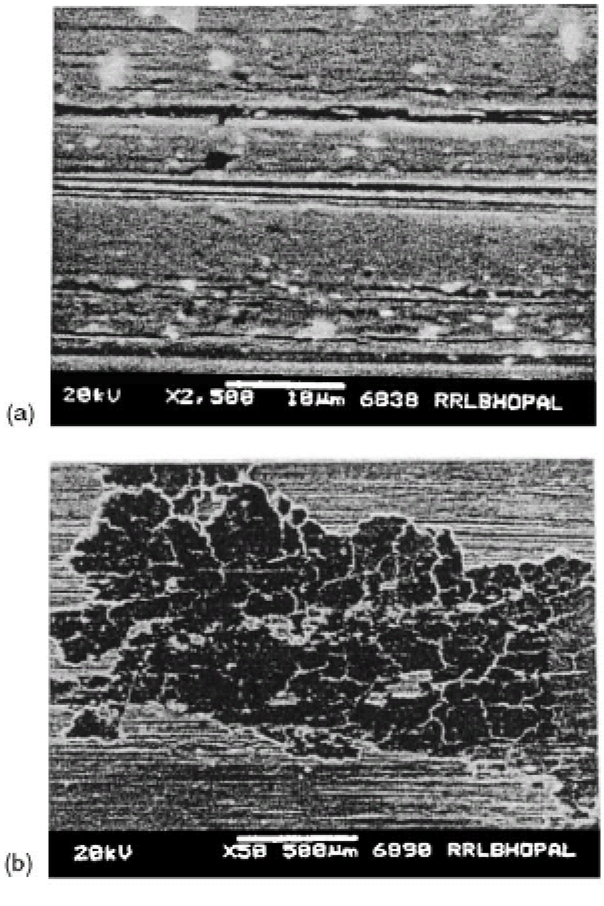
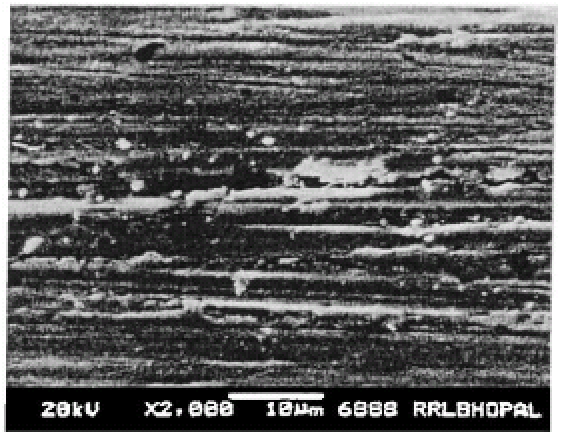


Fig.5 Typical worn surfaces of RFL4036 running against different counterface materials at 300N, 1000rpm, and 0.29 slip ratio; direction of friction from right to left. (a) RFL4036 against steel, (b) RFL4036 against aluminium, (c) RFL4036 against brass.

The worn surfaces of the mating materials against RFL4036 are shown in Fig.6. The original machining marks on the steel and aluminium surfaces in Fig.6a)-b) can be identified although both contact surfaces are covered by a layer of transfer film. The film on the steel surface is so thin that the original machine marks can be observed. The transfer film on the aluminium surface is so thick that the film has effectively covered the machining marks beneath the film. It was noted that there was no transfer film on the brass contact surface during the test. Instead, a large amount of brass debris mixed with RFL4036 was collected. Fig.6c) shows that the original machining marks have been replaced with irregular plough tracks during the wear process.

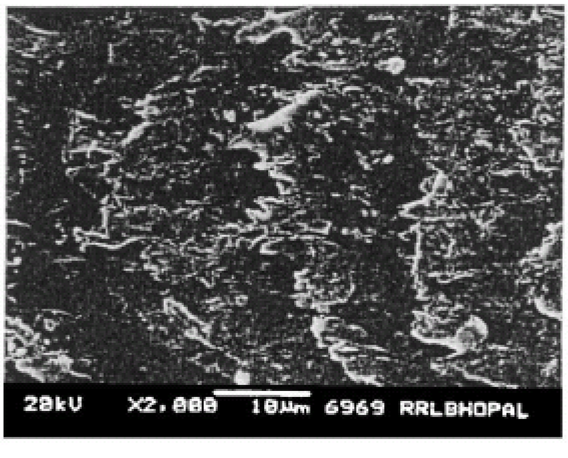




(c)

Fig. 6. Worn surface topography of aluminium, steel and brass discs running against RFL4036 at 300 N, 1000 rpm, and 0.29 slip ratio; direction of friction from right to left. (a) The steel worn surface, (b) transfer film on the aluminium worn surface, (c) typical brass worn surface.

Fig.7 shows typical worn surfaces of PA66 running against different counterface materials, steel, brass and aluminium. Fig.7a) shows that there is a layer of film and some flakes on the PA66 surface running against steel. This film had been sheared strongly during the friction process so that many small flakes started from the film and large pieces of film were pushed in the direction of the friction force. It is observed that many small flakes from the film have been transferred to the steel counterface to form a transfer film, as shown in Fig.8.a). The typical transverse cracks on the contact surfaces of the unreinforced polyamide 66 running each other [13-14] occurred when PA66 runs against all three different metallic materials, as shown in Fig.7b). It can be seen that a large portion of roll-like debris is attached to the surface and accumulates on the PA66 worn surface running against brass. Fig.7b) also shows that the surface suffered a very deep shear deformation and the surface material moved in the direction of friction. This deformed material was gradually rolled in the direction of friction. As a result, a piece of roll-like debris was formed, as shown in Fig.7b). In addition, very deep sheared surface material was transferred to counterface of brass, as shown in Fig.8b). Fig.7c) shows that material on the PA66 surface running against aluminium was smeared and formed a film on its own surface. It appears that the original machining marks on the aluminium counterface remain unchanged after $7x10^5$ running cycles, as shown in Fig.8c).



(a)

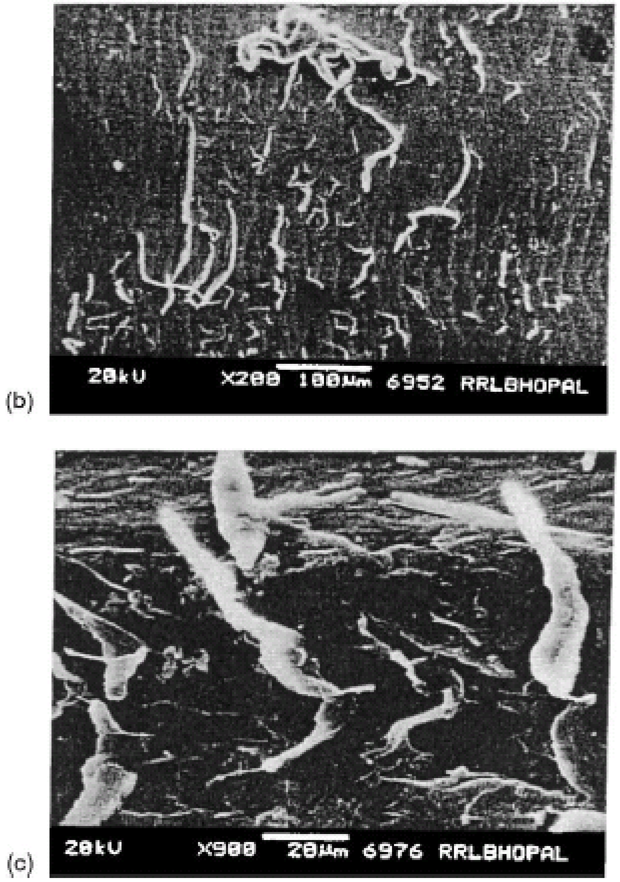
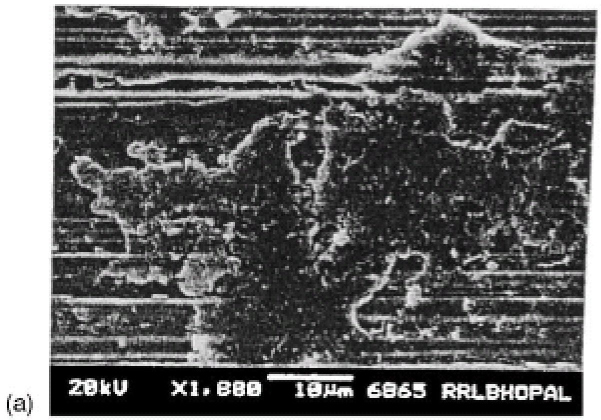


Fig. 7. Surface features of PA66 discs running against metal discs at 300 N, 1000 rpm, and 0.29 slip ratio. (a) PA66 surface running against steel direction of friction from right to left, (b) PA66 surface running against brass disc direction of friction from left to right, (c) PA66 surface running against Al direction of friction from right to left.



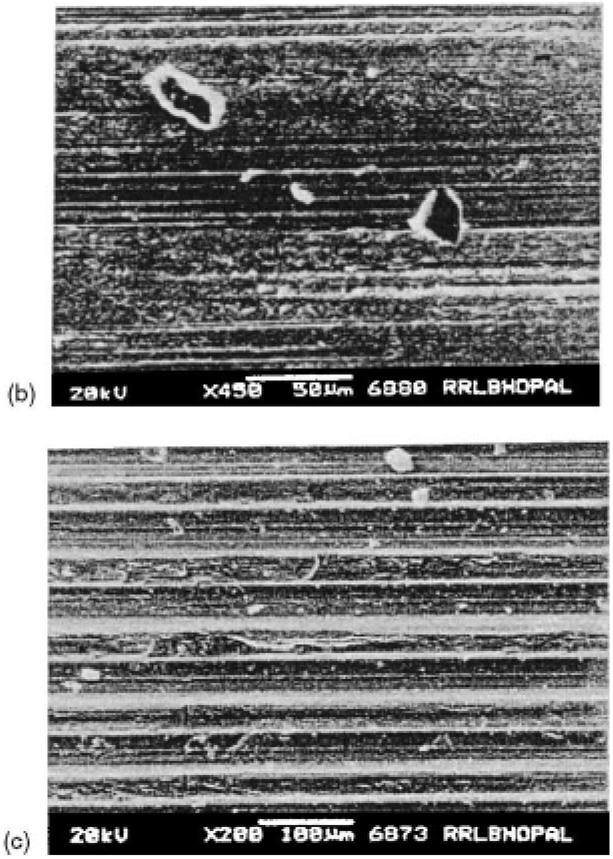


Fig. 8. General surface topography of steel, brass and aluminium running against PA66 at 300 N, 1000 rpm, and 0.29 slip ratio; direction of friction from right to left. (a) The steel worn surface, (b) the brass worn surface, (c) the aluminium worn surface.

4.2 Function of the thin film

The physical observations during the tests suggest that the low wear rates when RFL4036 runs against both steel and aluminium shown in Fig.3 are correlated with dark brown coloured and more polished material on the RFL4036 contact surface. This surface feature was related to a layer of thin film on the contact surfaces as observed by surface characterisation with SEM, as shown Figs.5-6. By contrast, the phenomenon of the brown and polished surface of RFL4036 during tests does not occur when RFL4036 runs against brass. It appeared that a high value for the wear rate was due to the absence of the film on the RFL4036 surface, as shown in Fig.5c), and that the low wear rates of RFL4036 running against both steel and aluminium shown in Fig.3 corresponded to the appearance of the thin film, as shown in Figs.8a)-b). The common function of the thin film on the RFL4036 worn surfaces running against steel and aluminium appeared to keep the wear rate low. It was noted that little wear debris was found for the RFL4036/steel and aluminium combinations. Before disruption of the transfer film on the aluminium surface, the film maintained a low and constant value of the friction coefficient between two discs, as shown in Fig.2. It was observed that the disruption of the transfer film corresponded to a steep increase of wear as shown in Fig.1.

The thin film on the PA66 contact surface running against steel and aluminum behaves quite differently. The film on the PA66 contact surface running against aluminium kept the wear rate very low although no transfer film was observed on the aluminium surface, as shown in Fig.8c). However, both the transfer film on the steel counterface and the film on the PA66 contact surface have not prevented PA66 from experiencing the highest wear rate of the three counterface materials, as shown in Fig.3. It was observed that the PA66 contact surface became dark-brown in colour and then the surface film on both surfaces started to disrupt, followed by a new layer of dark-brown colour. Many such cycles of creation and disruption of the surface film occurred during the test. There was no film and colour change observed when PA66 was tested against brass. Instead, much fibrous-like PA66 debris was observed and collected.

In case of brass disc, the lead exists as discrete particles in alloy known to act as weak points. It is suggested that the brass disc becomes prone to microcracking in the absence of a sufficient degree of heating. Glaeser [15] suggested that the cracks nucleate and propagate at and along the lead/matrix interfacial regions. This suggestion is in agreement with the results of the investigation. Under these conditions, lead particles pull out and become engulfed by the coarser debris particles. Thus, lead fails to smear and lubricate the contact surface and contributes to the wear of the matrix as reported by Prasad [16]. This led to a significantly higher wear of RFL4036 and PA66 against brass. The wear of brass was also observed to be much higher against RFL4036. The wear surface of PA66 when tested against brass revealed transverse cracks perpendicular to the sliding direction. X-ray analysis revealed the presence of lead particles within the debris which leads to abrasion of the PA66 and RFL4036.

On the other hand, more damage on the surface in terms of large size pits/craters were noted when RFL4036 was slid against brass. Fig.5c) shows a high amount of debris still on the worn surface during the test. Observation by SEM suggests that there were many broken fibres on the contact surface of the RFL4036. Those broken fibres were not covered with the transfer film so they caused effective abrasive wear on the brass contact surface. In fact, the brass experienced a slightly higher wear rate than the RFL4036 when they were tested as a mating pair and more brass debris than RFL4036 debris was observed. As can be seen in Fig.5c), a large amount of debris remained on the RFL4036 contact surface acting as abrasive particles during wear process. The brass particles, in return, resulted in severe wear on the RFL4036 surface so that more broken fibre debris would be produced. It is suggested that the wear between RFL4036 and brass is dominated by abrasive particles of broken fibre and brass.

The difference in the wear behaviour of the RFL4036 when running against the two different steels, EN24 and EN08, is attributed to the ability to form a transfer film on their contact surfaces. It was observed that the friction coefficient for the RFL4036/EN08 pair was around 0.32 and that for the RFL4036/EN24 combination fluctuated between 0.14 and 0.26. It appears that the lower friction coefficient for the RFL4036/EN24 pair is due to efficient lubricant function of the thin film on the EN24 surface. In other words, it is easier for the transfer film to form on the EN24 surface than on the EN08 surface, consequently, the wear rate of RFL4036 when running against EN24 steel is much lower than that running against EN08.

4.3 Thermal effect on formation of the thin film

The maximum surface temperature of two discs can be calculated by adding body temperature, flash temperature and ambient temperature [14]. Both body temperature of the specimens and ambient temperature were monitored during the tests using a thermocouple. The flash temperature was estimated using Blok's equation [17].

The maximum surface temperature was about 221^{o}C when PA66 ran against aluminium. This high surface temperature is very close to the melting point of 255^{o}C for PA66 and agrees well with the suggestion of a layer of liquid polyamide. When PA66 was tested against steel, the maximum surface temperature was approximately 205^{o}C. As shown in Fig.8a), the transfer film on the surface of steel disc was so patchy and thick that the transfer film could not survive long enough to provide sufficient lubrication between the contact surfaces of the two discs. However, PA66 behaved differently when it ran against brass although the maximum surface temperature was about 220^{o}C. There was no film on the contact surface of brass during the test, as shown in Fig.8b). Instead, a great deal of roll debris formed on the PA66 disc surface, as shown in Fig.7b). It appeared that brass prevented PA66 from smearing on the contact surface of the brass disc to form a thin film but generated rolls on the PA66 surface of the disc during the friction process. Without the protection of the thin film on the contact surface, the friction coefficient is very high and is in the range from 0.60 to 0.63. These rolls were not able to stay on the contact surface, and as a result, there was a great amount of roll debris found and collected during the test and the wear rate was much higher than that of the PA66/aluminium pair. It is suggested that not only surface temperature but also brass play important roles in tribological behaviour of PA66.

The maximum surface temperature when RFL4036 disc runs against steel and aluminium discs varies approximately from 144^{o}C to 170^{o}C. This range of temperature is outside the critical surface temperature of 206^{o}C, at which less film can be formed when unreinforced PA66 runs against itself [14]. Therefore, it is suggested that the range of surface temperature from 144^{o}C to 170^{o}C helps the formation of the thin film of matrix material, PA66, on the contact surface when RFL4036 runs against steel and aluminium in unlubricated, rolling-sliding contact. Similar to the case when PA66 ran against brass, it was noted that no film was observed on the brass surface when RFL4036 was tested against brass. It may be suggested that brass is not a suitable mating material for both PA66 and reinforced PA66(RFL4036).

5. Conclusions

1. The polyamide 66 composite (RFL4036) exhibited much lower wear rate than the unreinforced PA66 when running against steel counterfaces. However, when tested against brass and aluminium, PA66 exhibited lower wear than its composite. The friction coefficient of RFL4036 was always less than that of PA66 for all three counterface materials.

2. The wear and friction behaviour between PA66/RFL4036 and the metallic counterface materials depends on the ability of the metal surface to form a stable polymer transfer film.

3. BS2874 brass is unsuitable for use as a counterface material for PA66 and RFL4036 components in non-conformal rolling-sliding contact because of the failure of the transfer film. EN24 steel and 2011 aluminium are more likely candidate materials.

4. The surface treatment for steel has a significant effect on the wear rate of RFL4036. The wear rate of RFL4036 running against the Tufftride coated steel takes the lowest value of all three different surface treatments, Tufftride coated, manganese phosphate coated and untreated steel. The wear rates of RFL4036 running against the treated steel increases with an increase of slip ratio. However, the wear rate of RFL4036 running with the untreated steel takes its peak value at the slip ratio of 0.14 rather than at 0.29. At the slip ratio of 0.29, the wear rates of RFL4036 running against the manganese phosphate coated steel and the untreated steel are very close, but are much higher than that of RFL4036 running against the Tufftride coated steel.

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