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The wear and friction of short glass-fibre-reinforced polymer composites in unlubricated rolling–sliding contact

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The wear and friction behaviour of short glass-fibre-reinforced polyamide 66 composites running against each other, unlubricated, in non-conformal, rolling–sliding contact has been investigated. Both a wide range of loads and slip ratios and a range of samples with different fibre concentration and different crystallinity have been examined. Short glass-fibre reinforcement makes the polyamide 66 exhibit unique tribological behaviour. There is a high resistance to wear and friction which results from a significant "self-lubricating" property. A thin film layer exists on the contacting surfaces when two discs run against each other within the range of the test conditions. It is this thin film that plays a dominant role in the "self-lubricating" property of the composite. The formation of the thin film and the life of the composite depend on a complex of interactions between structure, strength and fibre concentration, and the specific conditions of load and slip ratio imposed. Under identical loading conditions, either lower fibre concentration or lower crystallinity cause the thin film to form continuously during the wear process so that the life of the composite may reach 6×10^6–10^7 cycles. It is suggested that the "self-lubricating" property may be used in the working period of engineering components rather than only during the temporary running-in period of machine elements.

1. Introduction
Short-fibre-reinforced polymer composites are now being used increasingly as engineering materials because of their high strength-to-weight ratio and ease of manufacture linked to excellent tribological properties [1–5]. Typical examples of non-conformal engineering components made from injection-moulded polymer composites are gears, cams and rolling element bearings. However, relatively little research into the wear mechanisms of polymer composites running against themselves has been carried out. Most applications simply use identical materials for both surfaces because of the design convenience in limiting the range of materials [6–11]. Most wear tests which only consider conformal sliding contact (e.g. pin-on-disc tests) simply do not match either non-conformal rolling–sliding contact or identical materials in contact. It is, therefore, very difficult to interpret the wear mechanisms of polymer composite gears [10–15] and to improve the performance of polymer composites in such applications. It is essential that polymer composites are tested under the appropriate conditions of unlubricated, non-conformal, rolling–sliding contact in order to establish the effects of reinforcement on their wear and friction behaviour.

Unreinforced semi-crystalline polymers, such as polyoxymethylene and polyamide (PA), display very low wear rates when sliding conditions are mild (in pin-on-disc tests), but melting of the frictional surface layer occurs easily during sliding [16, 17]. Under mild sliding conditions, the improvement of the wear in reinforced polymer composites is relatively small and the fibre reinforcement appears to decrease the wear resistance of the polymer under certain conditions [18, 19]. Although various fillers may be used to improve the tribological characteristics of polymers, short glass fibres are widely employed because not only is there improvement in the mechanical properties of the polymers but also the injection moulding process is still possible.

Although much work has been done on glass-fibre-reinforced polyamide (PA) it is based on the traditional test method of PA running against metal in sliding contact [18, 19]. Some early studies of the wear of polymers and polymer composites in unlubricated rolling–sliding contact concentrated on polymer composites against metals [17, 20, 21]. There appears to be little information on the tribological behaviour of polymer composites against polymer composites in non-conformal, unlubricated, rolling–sliding contact.

The purpose of this study was to investigate both the wear and friction behaviour of short glass-fibre-reinforced PA 66 composites running against themselves

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on a twin-disc machine. This paper will report the findings of this work and highlight those factors which contribute to high wear and friction performance under potentially arduous conditions.

2. Experimental procedure

2.1. Apparatus

The twin-disc wear testing machine used in our previous work [13–15] was again employed in this investigation. With this machine, measurements of both the frictional force and wear (as a change in radius) between two discs in contact can be made continuously. 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 [13–15, 22].

2.2. Materials and specimens

The material used was short glass-fibre-reinforced polyamide 66 (PA66). The proportions of glass fibre added were 40 wt % (LNP grade RF1008) and 30 wt %, respectively [3]. Because of shrinkage during injection moulding, the as-received samples did not contact each other uniformly. To ensure proper contact along the facewidth, all of the specimens were prepared by machining 20 μm from the moulded surface and polishing to a surface roughness of around 5 μm. Both the top and bottom discs were 30 mm diameter and 10 mm in facewidth.

2.3. Procedure

Tests were run for rolling speeds of 1000 r.p.m. and at a range of loads and slip ratios. Slip ratio is defined here as the ratio of sliding to rolling velocities and varies from 0 for pure rolling to 1.0 for simple sliding with one disc stationary. In mathematical form, 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 discs were cleaned with methanol after machining. 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 °C for 15 h to remove any absorbed water that might affect the measurement of wear, and then weighed. Finally, they were left under atmospheric conditions for about 2 weeks before testing 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, and were operated under dry, unlubricated conditions at ambient temperature (22 ± 1) °C until failure or for up to 10^7 rolling cycles. At the end of the test the specimens were again dried and weighed to measure the wear of each disc. With this drying procedure, the measurement of wear by weighing is accurate to about $\pm 10^{-5}$ g. Without drying, the accuracy appeared to be limited to $\pm 10^{-3}$ g. Direct measurement solely by using the data-logging system gave an accuracy equivalent to $\pm 3 \times 10^{-3}$ g [13–15]. Finally, the worn surfaces were observed in detail by using a Jeol JSM6300 scanning electron microscope.

3. Results

3.1. Wear behaviour

Typical wear and friction coefficient results as a function of number of cycles for moulded 40 wt % glass-filled PA 66 composites are shown in Fig. 1. These are for a running speed of 1000 r.p.m. and a normal load of 300 N. The wear is measured here as the separation of the disc centres while material on the disc surfaces is being removed during the tests.

For wear, these results show that the wear profile consists of four regions: a very short initial period; a nearly constant one; a very short unstable region and near linear wear phase with a period of significantly increasing wear. It can be seen that within the second period the wear curve is very flat and little wear is observed. It was noted that during this period, wear debris could hardly be observed. In contrast, the contact surfaces of the two discs appeared to become more and more polished. It appeared that there was a layer of film over the contacting surfaces which covered the glass fibres and caused this polished appearance. Fig. 1 also shows that the duration of this phase of wear varies with slip ratio. When the slip ratio increased from 0 (pure rolling) to 0.14, this period decreased from 10^7 to 10^5 cycles and it decreased again to 10^4 cycles at a slip ratio of 0.28.

The third period is short no matter how high the slip ratio. It was noted that this period corresponded to the surface film peeling, with wear debris being detached from the surface. Following this film peeling phase, it can be seen that the wear increased sharply and it was noted that more and more wear debris was detached. Once the film had been completely removed the wear entered the fourth period – the severe wear region. As shown in Fig. 1, in the fourth period, the wear increased sharply and about 0.25 mm was worn

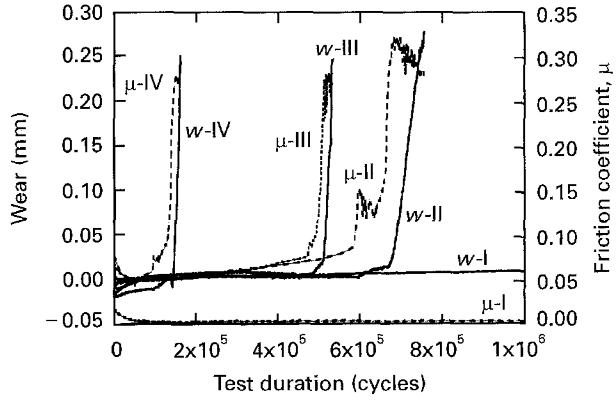

Figure 1 Wear, *w*, and friction coefficient, μ, of 40% short-glass-fibre-reinforced PA 66 composite (RF1008) running at 300 N normal load and 1000 r.p.m. I, 0.00 slip; II, 0.04 slip; III, 0.11 slip; IV, 0.14 slip.

away in 10^2–10^4 cycles (that is total wear for both discs). The wear in this period was so high that it caused eventual destruction.

Fig. 2 shows typical wear and friction results for moulded 40 wt % glass-fibre polyamide composites for a running speed of 1000 r.p.m. and a fixed slip ratio of 0.04. Similar to the characterization of wear periods in Fig. 1 above, four periods of wear behaviour can be clearly seen. The length of the second, "non-wear", period depended on the load on the contacting surfaces of the discs. When the load increased from 200 N to 400 N, this period.decreased from 10^6 to 10^4 cycles. The fourth period was also a region of rapidly increasing wear. It can be seen that the gradient of wear against number of cycles in this period varies with load. The higher the load the greater the gradient and wear rate. In the severe wear region the gradient of the wear curve in Fig. 2 is less steep than that in Fig. 1. In other words, severe wear of this material is more sensitive to slip ratio than to load.

3.2. Friction behaviour and friction coefficient, μ

The friction force was found by measuring the tangential sliding force on the lower disc using a displacement transducer. The (RMS) accuracy of the measurement is about 3.0 N [13–15]. The friction coefficient can be calculated as the force divided by the normal load and is recorded during the tests. As shown in Figs 1 and 2, except for the case of pure rolling, the graphs of the friction coefficient, μ, can also be divided into four regions: a very short initial region; a linear increasing region; a high value build-up region and a high value region. In the first region, the friction coefficient, μ, decreased from about 0.1 to about 0.05. Then it increased nearly linearly in the non-wear region where its value was less than 0.1. During the film peeling process (the third wear period), the friction coefficient, μ, increased steeply to about 0.3. In the fourth region, it retained the high value built up in the third region although this varied slightly about the value of 0.05 due to vibration during the tests. This high value region corresponds to severe wear. As shown in Fig. 1, the friction coefficient varied between 0.3 and 0.25 when the slip ratio increased from 0.04 to 0.14. On the other hand, as shown in Fig. 2, it decreases rapidly from 0.32 to 0.2 when the load increased from 200 N to 400 N. Thus the friction coefficient, μ, in the severe wear region of this material is more sensitive to load than to slip ratio, in contrast to the wear behaviour discussed above.

3.3. Wear rate

Wear rate is defined here as the average depth of material removed from each disc per rolling cycle. This definition was chosen rather than the Archard wear coefficient [23] as being more appropriate for these load conditions [15]. Fig. 3 shows how this wear rate for 40% short glass-fibre-reinforced PA 66 composites varies with slip ratio for a fixed normal force of 300 N and constant rolling speed. It can be seen that, except for the case of pure rolling, all of the wear rates for different slip ratios are greater than approximately 10^{-4} μm cycle^{-1}. The wear rate increases nearly linearly from 10^{-4} μm cycle^{-1} to 10^{-3} μm cycle^{-1} as the slip ratio increases from 0.04 to 0.28. However the wear rate is within the same order of magnitude, that is 10^{-4} μm cycle^{-1}, because all of these results came from the severe wear region described above. For pure rolling, because the wear, as shown in Figs 1 and 2, has not reached the severe wear region and the polished surface has not been removed (although it has run for over 10^7 cycles), the wear rate is much lower than that in the severe region. It is 1.0×10^{-7} μm cycle^{-1} which is lower by a factor of three than that in the severe wear region.

Fig. 4 shows the effect of normal load on the wear rate of the material RF1008 at a fixed slip ratio of 0.04 and a constant running speed of 1000 r.p.m. It can be seen that the wear rate increases uniformly on a logarithmic scale from 10^{-5} μm cycle^{-1} to 3×10^{-4} μm cycle^{-1} as the normal load increases from 100 N to 500 N. All the results for wear rate shown in Fig. 4 were for severe wear characterized by the steeply rising parts of the curves in Fig. 2.

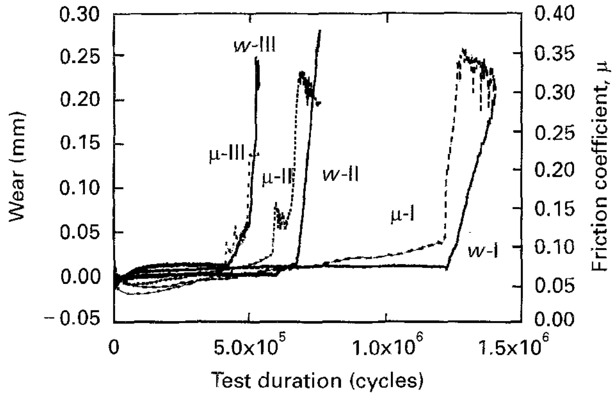

Figure 2 Wear, *w*, and friction coefficient, μ, of 40% short glass-fibre-reinforced PA 66 composite (RF1008) running at 0.04 slip ratio and 1000 r.p.m. I, 200 N; II, 300 N; III, 400 N.

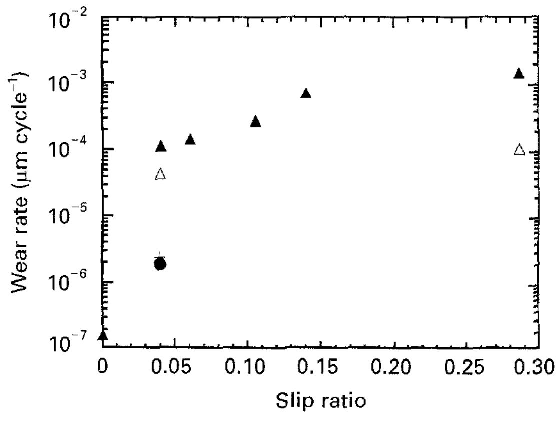

Figure 3 Wear rate versus slip ratio for PA 66 composites running against themselves. Normal load 300 N, and running speed, 1000 r.p.m. (▲) 40 wt % fibre PA 66 composite, RF1008; (●) 30 wt % fibre PA 66 composite, bar A; (△) 30 wt% fibre PA 66 composite, bar B; (+) unreinforced PA 66, R1000.

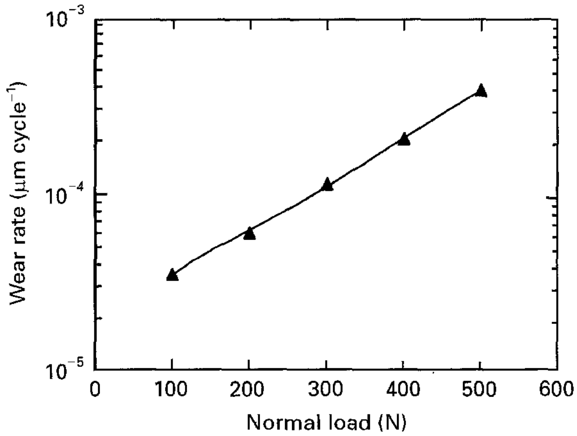

Figure 4 Wear rate versus load for PA 66 composite (RF1008) running against itself. Slip ratio 4%, and running speed 1000 r.p.m.

4. Discussion
4.1. Surface characterization
As described above, the majority of material loss is in the severe wear region as defined by Figs 1 and 2. This is where the thin surface layer has been disrupted and the wear rate is dominated by the ability or otherwise of this film to be formed continuously during wear and to be retained on the surface. Scanning electron microscopy, as shown in Figs 5–10, confirms this suggestion.

Fig. 5 shows the initial surface, machined and polished for tests. It can be seen that most fibres are uncovered and oriented randomly.

A section through the worn surface region in Fig. 6 shows the worn surface in the second (or "non-wear") region. It can be seen that there is a layer of film which covers or partly covers the fibres and the proportion of fibres on the surface is generally greater than that seen initially. This suggests that the proportion of fibres beneath the surface layer increased during the second wear period until the film peeled off and produced a fibre-rich sub-surface. Fig. 7 shows the thickness of the surface film on the worn surface of Fig. 6 which can be observed by sectioning parallel to the sliding direction. This thickness of the film varied typically from 2–5 μm, as shown in Fig. 7.

When the film was eventually disrupted, the worn surface features showed two trends in behaviour. One is shown in Fig. 8 where all the fibres on the surface are both exposed and randomly distributed and the matrix appears stretched. The other, as shown in Figs 9 and 10, is where the fibres are either wholly or locally orientated. The degree of fibre orientation on the surface was strongly affected by the slip ratio. When the slip ratio reached 0.28 with 300 N load and at 1000 r.p.m. running speed the fibres on the surface were highly aligned, as shown in Figs 9 and 10, and approximately parallel to the friction force. Figs 9 and 10 also indicate that both long and short broken fibres are visible parallel to the friction force. It appears that these broken fibres can move on the surface during alignment from an initially random distribution as shown in Fig. 5. When the slip ratio is less than 0.28 at the same load and running speed the fibres are mainly distributed randomly. It is very interesting that this phenomenon of aligned fibres is quite similar to that seen in short glass-fibre-reinforced polyacetal in pure sliding tests [19]. However, unlike short glass-fibre-reinforced polyacetal [19], for RF1008, the aligned broken fibres shown in Fig. 9 do not remain on the surface indefinitely. As the film peeled, they were either expelled out as debris or rebedded into the PA 66 matrix beneath them. Eventually, all the highly aligned broken fibres disappeared and once severe wear commenced the surface features had changed as shown in Fig. 8, which is similar to the surface features at lower slip ratios after disruption of the film. It can be seen that the surface shown in Fig. 8 has a high concentration of broken and random fibres and that most of the fibres are uncovered.

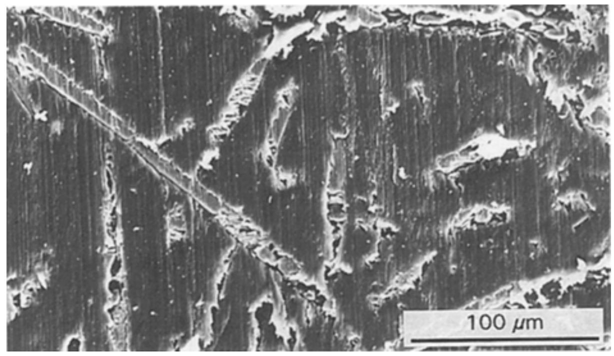

Figure 5 An SEM image of an initial specimen surface machined and polished for tests.

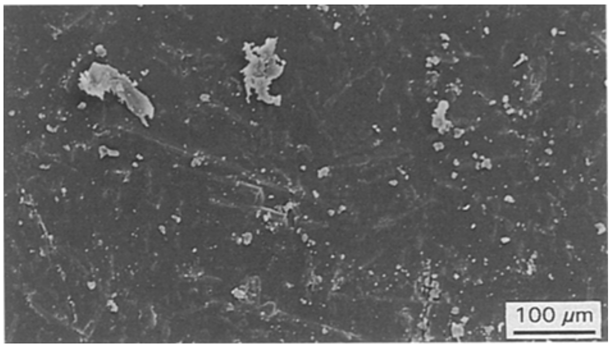

Figure 6 Contact surface in the "low-wear" region, at a slip ratio of 0.04, normal load of 300 N and running speed of 1000 r.p.m.; direction of friction from bottom to top.

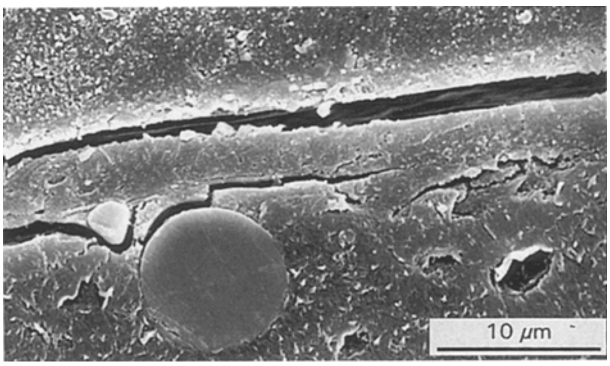

Figure 7 Thickness of the thin film during the low-wear region, at 0.04 slip ratio, 300 N normal load and 1000 r.p.m. running speed; direction of friction from left to right.

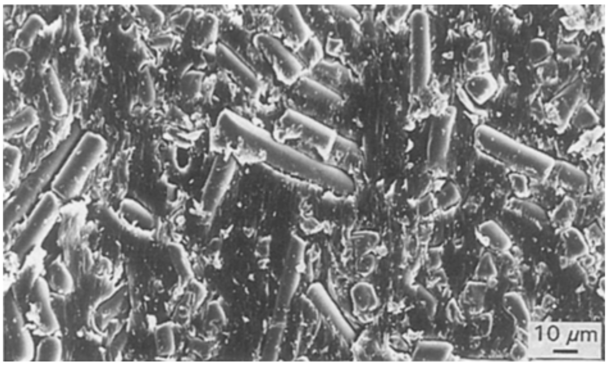

Figure 8 Surface features after disruption of the thin film, at 0.04 slip ratio, 300 N normal load and 1000 r.p.m. running speed; direction of friction from bottom to top.

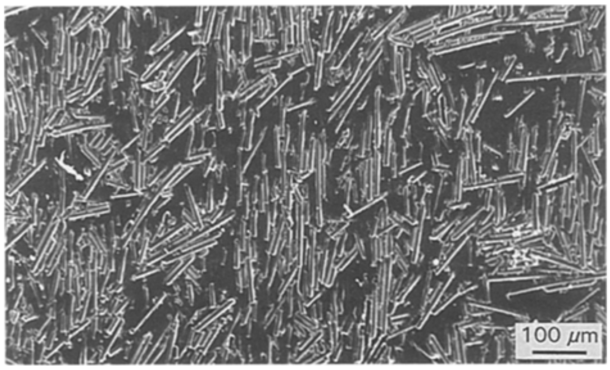

Figure 9 Highly aligned broken fibres on the worn surfaces after disruption of the thin film, at 28.6% slip ratio, 300 N load and 1000 r.p.m. running speed; direction of friction from bottom to top.

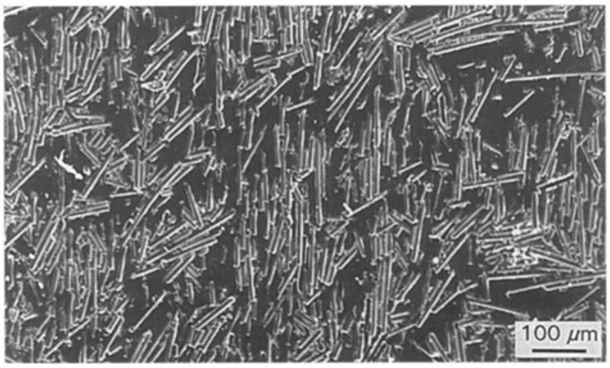

Figure 10 Locally aligned fibres on the worn surfaces of high crystallinity after disruption of the thin film, at 28.6% slip ratio, 300 N normal load and 1000 r.p.m. running speed; direction of friction from top to bottom.

4.2. Function of the thin film

The function of the thin film in short glass-fibre-reinforced PA 66 may be determined by a comparison between the wear behaviour shown in Figs 1 and 2 and the surface topography of the worn surfaces shown in Figs 6–8. It can be seen that the flat regions of the curves (both low friction and invisible wear regions) shown in Figs 1 and 2 always correspond to the appearance of the thin film and that the extremely sharply increasing wear regions in Figs 1 and 2 are correlated with film disruption as shown in Figs 8–10. It appears that the function of the thin film on the worn surfaces is to act as a kind of lubricant which decreases the friction between both contact surfaces significantly and subsequently keeps the wear rate low. Because this lubrication is created from the contact surfaces rather than from the application of external lubricant, the phenomenon may be regarded as self-lubricating behaviour.

With this film on the surface, the composite can be protected so significantly that little wear debris can be found and the wear cannot be measured with a transducer to an accuracy of 1 μm. The wear rate determined by weighing is around 10^{-6} μm cycle^{-1} and the friction coefficient, μ, can be below 0.1. The "self-lubricating" property of the PA 66 composite here is similar to that of the transfer film in unreinforced PA 66 when it runs against metals [17, 24].

The thin film on the contact surfaces was discoloured significantly after tests at higher loads and slip ratios, indicating surface degradation. This might suggest that contact at high loads takes place with effectively a liquid nylon lubricant [17]. However, under conditions of low load and slip ratio, the thin film is also discoloured and so the degradation is unlikely to be due simply to melting of the nylon. The extent of the colour change varies with the number of cycles, and it appears that repeated contact between the thin films leads to surface degradation. This requires further investigation.

Because of the low friction coefficient, μ, as shown in Figs 1 and 2, the shear stress at the interface between the films should be low. This low shear stress between the films may play an important role in the self-lubricating property of the composites. Once the film has been removed from the contact surfaces, the "self-lubricating" property is destroyed and the wear rate increases sharply to about 10^{-4} μm cycle^{-1} and the friction coefficient, μ, can rise three-fold to 0.3. This phenomenon in glass-fibre-reinforced PA 66 is similar to that in other polymer composites [25]. However, in contrast to Lancaster's suggestion [25], this self-lubricating property does not offer merely temporary protection but may remain for over 10^7 cycles if fibre concentration, thermal history, load and slip ratio can be controlled properly.

4.3. Formation of the thin film

The results presented here suggest that the wear of short glass-fibre-reinforced polyamide 66 depends on a complex of interactions between structure, strength and fibre concentration, and the specific conditions of the loads and slip ratios imposed. In order to understand how this film is formed, tests were done with different fibre concentrations and thermal histories. For unreinforced PA 66 running against itself under the same conditions as composites (300 N normal load, 0.04 slip ratio 1000 r.p.m. running speed), no film was observed in the SEM. Although the wear rate is low, more serious damage has been noticed. Because the sample is over stressed due to higher loads, the contacting surfaces show a characteristic series of macrocracks perpendicular to the sliding direction and further running causes very large wear debris and catastrophic fracture. This will be reported more fully later. It appears that this thin film is only formed on short glass-fibre-reinforced PA 66 composites rather than on the unreinforced matrix materials.

Two mechanisms for the formation of the film are suggested by Figs 6 and 7. One is that fibres are rebedded deeper and deeper in the polymer matrix until they become covered with polyamide film. The other is that the matrix material around the fibres is stretched or smeared during the friction procedure.

The first mechanism is limited by fibre concentration. As shown in Fig. 3, under the same test conditions (300 N normal load, 0.04 slip ratio and 1000 r.p.m. running speed), the wear rate of the composite with 40% glass fibre is higher by a factor of two than that of the same composite with 30% glass fibres. Such a large difference in wear rate could be due to the lifetime of the self-lubricating film. The film in the higher fibre concentration material lasted for only about 6.0×10^5 cycles (as shown in Figs 1 and 2) and then was disrupted as shown in Fig. 8. By contrast, that in the lower fibre concentration material lasted for over 4.0×10^6 cycles and still remained (as shown in Fig. 6) without any indication of significant film peeling. It is suggested that high fibre-concentration polyamide can easily cause disruption of the self-lubricating film because there is less room for the fibres to be bedded into the matrix. This suggestion is supported by the observation of debris from the contact surfaces. Figs 11 and 12 show sections of the large debris expelled from the contact surfaces. These large pieces of debris are about 1.5 mm long and 1.0 mm wide and their shape is irregular. Fig. 11 shows a section of debris from the 40% glass fibre composite and Fig. 12 shows that of debris from the 30% glass fibre composite. The compatibility of higher fibre-concentration material with fibre debris appears to be much lower than that of lower fibre-concentration material, so that it is difficult for the fibres to be bedded into the matrix with higher fibre concentration.

The second mechanism of film formation is related to the permanent deformation of the matrix material, that is the ductility of PA 66. To study this mechanism, some work has been done by changing the crystallinity of the composites whilst keeping the fibre concentration constant. As shown in Fig. 3, the wear rates of both (30% glass-fibre-reinforced PA 66) composites tested is very different. There is a large difference in percentage crystallinity as measured by differential scanning calorimetry (DSC). Bar A has a crystallinity of 27% but the crystallinity of bar B is 45%. The difference in modulus of the matrix material is about 100%, and in the yield stress is approximately 40% [26]. It appears that it is more difficult for fibres to be bedded into the PA 66 matrix of higher crystallinity and 100% higher stiffness. As a result, unbedded fibres may act as hard asperities on the contact surfaces and abrasive wear is inevitable. It is also suggested that it is very difficult for the matrix of PA 66 with higher stiffness and 40% higher yield stress to be stretched and smeared on the contact surfaces to form a continuous layer of matrix in order to provide self-lubricating properties during wear. These two suggestions are supported by Fig. 3. It can be seen that the

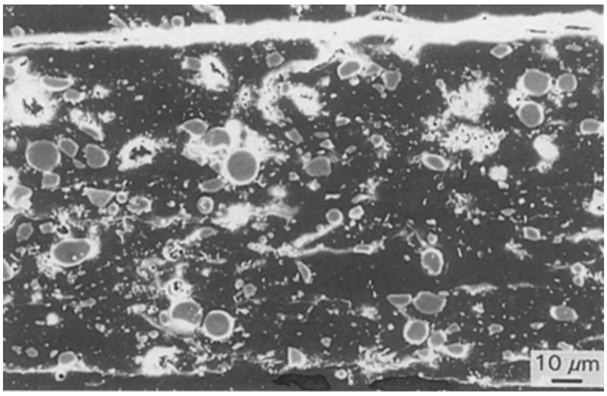

Figure 11 An SEM image of the section view of the largest piece of worn debris from the higher fibre-concentration PA 66 composites.

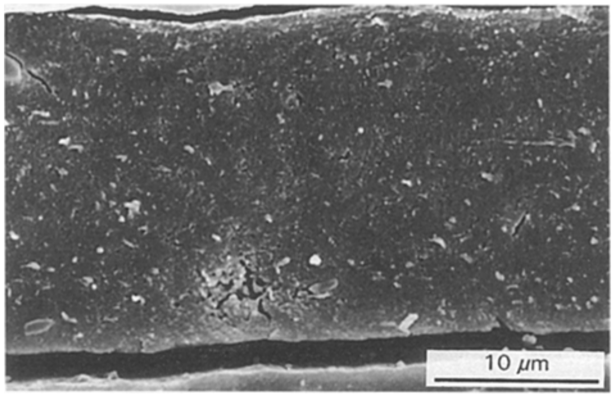

Figure 12 An SEM image of the section view of the largest piece of worn debris from the lower fibre-concentration PA 66 composites.

wear rate of bar A with lower crystallinity is only just above 10^{-6} μm cycle^{-1} and that of bar with higher crystallinity has reached 4.0×10^{-5} μm cycle^{-1}. It again appears that such a large difference in wear rates is due to the life of the thin surface film. For the sample with lower crystallinity, the film lasted over 4.0×10^6 cycles without significant disruption. For the sample of bar B with higher crystallinity, the life of the film on the wear surface was just 6.0×10^5 cycles.

5. Conclusions

1. The wear and friction of short glass-fibre-reinforced polyamide 66 composites running against themselves in unlubricated rolling–sliding contact have been investigated under wide range of loads and slip ratios and with a range of materials with different fibre concentrations and different crystallinities. Both the coefficient of friction and the wear rate are very low under a wide range of loads and slip ratios.

2. The high resistance to wear and friction results from a significant "self-lubricating" property. A thin film layer on the contact surfaces when two discs run against each other, plays a dominant role in the "self-lubricating" behaviour of the composite. When the contact surfaces are separated by this film, the wear rate is rather low, approximately 10^{-6} μm cycle^{-1}, and the friction coefficient, μ, is below 0.1. However, once this layer has been removed, the "self-lubricating" property is destroyed so that the wear rate

increases sharply by an approximate factor of two, to 10^{-4}–10^{-3} μm cycle^{-1} while the friction coefficient, μ, remains below 0.28–0.35.

3. The formation of the thin film and the life of the composite depend on structure, strength and fibre concentration, and on the loads and slip ratios. Under identical loading conditions, either lower fibre concentration or crystallinity cause the film to form continuously so that the life of the film may reach 6×10^6–10^7 cycles.

4. A fibre-rich layer is also formed beneath the film during the friction and wear process. Combined with its covering of the thin film, this fibre-rich layer plays a vital role in supporting part of the applied load and reducing the wear rate of the matrix material.

5. The life of this film is so great that it should not be treated merely as a temporary phenomenon occurring only during the "running-in" period. This self-lubricating property can be used during the normal working life of engineering components.

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