The effect of glassfibre, graphite and MoS₂ on the tribological performance of a liquid crystalline polymer*

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Abstract

A thermotropic liquid crystalline polymer (LCP) with a high melting point of approximately 400 °C, unfilled and filled with glassfibre, MoS₂ or graphitic carbon was tested in dry sliding contact with steel. Three different test methods were applied, *i.e.* measurement of coefficient of friction and specific wear rate *vs.* contact temperature; determination of load-carrying capacities at three different values of sliding speed, and friction and wear behaviour in 20 h tests under relatively severe conditions of load and sliding speed.

It turned out that only glassfibre-containing materials perform adequately as dry-running bearing materials, provided that the contact temperature quickly rises above a critical value of the order of 125–140 °C. In load-carrying capacity tests and in 20 h tests under severe conditions, adding graphitic carbon to glassfibre-containing LCP is particularly beneficial, as this substantially increases the thermal diffusivity of the material. Thus it is concluded that glassfibre- and graphitic-carbon-containing LCP is perfectly suitable for use as a dry-running bearing material at elevated temperatures.

1. Introduction

In the past decade, many new types of high-temperature-resistant thermoplastic polymers have been developed. These new materials often offer, next to continuous high temperature resistance (up to 250 °C), inherent flame retardancy, superior resistance to aggressive chemicals and good mechanical properties, both static and dynamic. An increasingly important class of polymers is formed by the so-called thermotropic (or melt-processable) liquid crystalline polymers (LCPs) [1–6], some of which are commercially produced.

Thermotropic LCPs are polymers with a rigid backbone, usually consisting of aromatic structural units (so-called mesogenic units) in an extended chain conformation. Currently available LCPs are either copolyester or copolyesteramides, without aliphatic segment. When properly processed (*e.g.* during injection moulding), the particles obtained show a high degree of molecular orientation and order, especially in the direction of flow and thus possess a highly characteristic, material-intrinsic and process-induced

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layered morphology [7]. Since the late 1980s, there has been a growing interest in the tribological performance of LCPs and their short-fibre composites [8–10].

When aiming at a good tribological performance, short glassfibres or carbon fibres may improve the mechanical strength (and thus the resistance against shear forces in the surface region) still further, while polytetrafluoroethylene, MoS_2 and graphitic carbon are to be chosen if friction is to be reduced. The latter under the condition that the shear strength of the polymer is in a zone directly below the contact surface does not seriously decrease as a result of adding a friction-reducing material [11]. Under favourable conditions, very low specific wear rates of the order of $10^{-7} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ may thus be achieved [10].

It was the objective of the present work to study the tribological effects of compounding LCP with glassfibre, alone or in combination with graphitic carbon or MoS_2 in some detail.

Preferably, materials should be characterized with respect to a well-defined application. In that case the type of application determines the type of test that should be performed. In the present case, however, a specific application was not available. Therefore we tried to characterize the LCPs in more general terms, *i.e.* with respect to their thermal and mechanical loadabilities and their wear behaviour under relatively severe conditions of applied pressure and sliding speed. To that purpose, the following tests were performed: (1) measurement of the coefficient f of friction and the specific wear rate k as a function of the contact temperature T_c , at a sliding speed v of 0.1 m s^{-1} and an apparent contact pressure p of 1.5 N mm^{-2} ; (2) determination of the load carrying capacity p_{max} at sliding speeds v of 0.1 , 0.5 and 3 m s^{-1} and freely varying contact temperature; (3) determination of the wear rate at $p = 5 \text{ N mm}^{-2}$ and $v = 0.25 \text{ m s}^{-1}$.

2. Experimental details

In the above tests the TNO tribometer was used. This test rig has been described on several previous occasions (see for example ref. 12).

In the present case, flat rectangular ($10 \text{ mm} \times 10 \text{ mm} \times 3 \text{ mm}$) test pieces, taken out of the central part of injection-moulded bars of the polymers to be characterized, were pressed under a known normal force F (*i.e.* a known apparent contact pressure p) against the flat surfaces of rotating steel discs (Fig. 1). During the tests, friction between the test piece and the disc could be measured with a torque shaft, provided with strain gauges. The temperature of the disc at 1.0 mm from the surface was measured with a thermocouple 0.4 mm in diameter, inserted in the disc material (ball

Fig. 1. Schematic drawing of the specimen couple.

bearing steel AISI 52100, hardened to a Vickers hardness of 700 kgf mm⁻²). The specimens were surrounded by an air-tight casing, into which clean air could be introduced.

2.1. Measurement of f vs. T_c and k vs. T_c curves

The measurement of f vs. T_c curves has been described elsewhere [11–13]. Briefly, it is performed as follows. At specific values of F (or p) and v , the contact temperature T_c reaches an equilibrium value $T_{c,e}$, usually in less than 5 min. When this is the case, T_c is increased further by computer-controlled inductive heating of the steel disc. Thus, from $T_c = T_{c,e}$ on, T_c becomes an independent variable. Additional variables are the starting temperature $T_{c,min}$ ($> T_{c,e}$), the rate of temperature increase dT/dt and the maximum testing temperature $T_{c,max}$. As T_c increases linearly with time, f is also measured as a function of time or, at constant sliding speed, as a function of sliding distance d .

In the present case possible changes in thickness of the polymer block were also continuously recorded as a function of time by means of a sensitive differential transformer. The changes in thickness, thus obtained, were due to a combination of thermal effects and wear. By subtracting the results obtained in tests performed at the same value of dT_c/dt but at $v = 0$ m s⁻¹ (thermal effects, but no wear), it was possible to obtain a close estimate of the amount of volume wear ΔV as a function of time. Next the values of the specific wear rate k , calculated over 30 min periods, were found from

$$k = \frac{\Delta V}{Fd} \quad (1)$$

The present tests were performed under the following conditions: roughness of steel disc surface $R_a = 0.1$ μ m (centre-line average), $F = 150$ N, $p = 1.5$ N mm⁻², $v = 0.1$ m s⁻¹, $T_{c,min} = 50$ °C, $dT_c/dt = 15$ °C h⁻¹ and $T_{c,max} = 300$ °C. The experiments were performed in an environment of air of 20 ± 1 °C and relative humidity of $50 \pm 10\%$.

2.2. Determination of p_{max} at $v = 0.1, 0.5$ and 3 m s⁻¹

In determining the load-carrying capacity p_{max} as a function of sliding speed v , the tests were started at a given pressure level, i.e. 1.5 N mm⁻², 0.5 N mm⁻² or 0.25 N mm⁻² at sliding speeds of 0.1 m s⁻¹, 0.5 m s⁻¹ and 3 m s⁻¹ respectively.

From the starting value on, the pressure was increased in steps, each step adding 25% to the preceding value. At each pressure level a 1 h test was performed, in which the coefficient of friction and the wear rate were recorded continuously with time. If a transition in either friction or wear occurred, which usually happened directly after increasing the pressure, the load-carrying capacity p_{max} was taken to be equal to the preceding pressure level.

2.3. Determination of the wear rate at $p = 5$ N mm⁻² and $v = 0.25$ m s⁻¹

In additional experiments, coefficients of friction and wear rates were measured at $p = 5$ N mm⁻², $v = 0.25$ m s⁻¹ and T_c values of 150 or 20 °C. In most cases the test material failed because of severe wear within a few seconds after application of loading. However, if this did not happen, the test duration was 20 h.

3. Materials

In accordance with the objective of the work the materials in Table 1 were characterized. The LCP base material was based on biphenol chemistry. After com-

TABLE 1

Codes for materials

Material	Code
LCP, unfilled (experimental material of DSM Research)	LCP
LCP with 10 wt.% MoS ₂	LCP-M
LCP with 10 wt.% MoS ₂ and 15 wt.% graphitic carbon	LCP-M-C
LCP with 15 wt.% glassfibre	LCP-G
LCP with 15 wt.% glassfibre and 10 wt.% MoS ₂	LCP-G-M
LCP with 15 wt.% glassfibre and 15 wt.% graphitic carbon	LCP-G-C

TABLE 2

Mechanical properties of liquid crystalline polymer compounds, measured at 20 ± 1 °C and $50 \pm 10\%$ relative humidity

Material	Flexural modulus (GPa)	Flexural strength (MPa)	Izod impact strength (kJ m ⁻²)	Rockwell hardness (HR)
LCP $\perp$	3.7	81	7.3	100
	12.9	138	22.7	
LCP-M $\perp$	2.0	50	7.4	95
	12.1	140	13.4	
LCP-M-C $\perp$	3.2	77	4.9	96
	12.4	148	5.8	
LCP-G $\perp$	3.8	92	5.7	96
	13.3	154	5.7	
LCP-G-M $\perp$	2.8	52	3.2	97
	10.2	117	4.6	
LCP-G-C $\perp$	3.5	77	4.2	104
	11.3	141	4.3	

pounding, the granulate was dried and processed into end-gated rectangular bars with dimensions 158.0 mm $\times$ 12.7 mm $\times$ 3.2 mm, using an injection-moulding machine of the Arburg Company (type 220-90-350; screw diameter, 22 mm; clamping force, 35 tonf). The cylinder temperature was set at 410 °C and the mould temperature at 200 °C. A screw speed of 250 rev min⁻¹ and an injection speed of 130 mm s⁻¹ were used. Depending on the compound type, cycle times between 39 and 41 s were realized.

Some material properties of the above compounds are presented in Table 2, while Table 3 lists thermal diffusivity χ values, measured at 25 °C and 100 °C respectively. It can be seen that there are pronounced differences between the different compounds, particularly at $T=100$ °C. At that temperature LCP-G-C clearly has the highest χ value. It is to be expected that the differences become even more pronounced at still higher temperatures.

Figures 2 and 3 show scanning electron microscopy (SEM) pictures, taken at different magnifications, of cryogenic fracture surfaces of LCP-G-C. The layered structure of the material and the short glassfibres can be seen clearly. In all cases the orientation

TABLE 3

Thermal diffusivity χ values of liquid crystalline polymer compounds

Material	χ (mm ² s ⁻¹)	
	$T=25 \pm 1$ °C	$T=100 \pm 2$ °C
LCP	0.09	0.04
LCP-M	0.09	0.05
LCP-M-C	0.11	0.10
LCP-G	0.11	0.07
LCP-G-M	0.15	0.09
LCP-G-C	0.15	0.15

Fig. 2. SEM picture of fracture surface of LCP-G-C. (Original magnification, 20 $\times$.) Fig. 3. SEM picture of fracture surface of LCP-G-C. (Original magnification, 100 $\times$.)

of LCP and glassfibres was parallel to the contact surface. All materials were tested in two ways, *i.e.* with the orientation of the LCPs perpendicular to (indicated with a $\perp$ sign) or parallel to the direction of movement (indicated with $\parallel$ sign).

4. Results

The surfaces of the steel discs remained unchanged throughout the tests, *i.e.* scratching, however light, did not occur. In some cases a thin layer of transferred polymer could be observed with the unaided eye. This did not correlate with friction and wear results.

4.1. f vs. T_c and k vs. T_c curves

Figures 4–7 present a survey of, the f vs. T_c and the k vs. T_c respectively, that were obtained with the above 12 different LCPs. They show a clear and highly remarkable effect, *i.e.* an extremely beneficial influence of glassfibre. This effect does not depend on the orientation of the LCP molecules (*i.e.* $\perp$ or $\parallel$). In fact it is found that at the beginning of the test, *i.e.* in the temperature region from 50 to about 100 °C, all materials behave similarly, *i.e.* they show a relatively high coefficient f of friction,

Fig. 4. Coefficient f of friction *vs.* contact temperature T_c curves, obtained with the six LCPs with $\perp$ fibre orientation.

Fig. 5. Coefficient f of friction vs. contact temperature T_c curves, obtained with the six LCPs with $\parallel$ fibre orientation.

Fig. 6. Specific wear rate k *vs.* contact temperature T_c curves, obtained with the six LCPs with $\perp$ fibre orientation.

Fig. 7. Specific wear rate k vs. contact temperature T_c curves, obtained with the six LCPs with $\parallel$ fibre orientation.

Fig. 8. Coefficient f of friction *vs.* time t for LCP-G-C $\perp$ and $\parallel$, tested at 150 °C disc temperature.

of the order of 0.5–0.6, and a specific wear rate k of the order of $5 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$.

For the LCPs without glassfibre this period is terminated by a transition to a regime of severe wear ($k > 40 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$). With LCP and LCP-M this transition is accompanied by a substantial increase in f , *i.e.* to a level of 0.8–1.0; with LCP-M-C, f remains about the same. In these cases the tests had to be terminated before T_c reached its maximum value of 300 °C, because the test specimens were completely worn away. This behaviour disqualifies these materials for use as bearing materials under conditions of dry sliding against steel.

For the LCPs with glassfibre, f as well as k decrease dramatically upon reaching a critical value of T_c . From this it can be concluded that these materials are potentially good bearing materials for application under conditions of dry sliding against steel at elevated temperatures (*e.g.* $T_c > 150$ °C).

A detailed analysis of Figs. 4–7 is possible with the help of Table 4. This table shows the value of the contact temperature T_{c,f^*} at which the transition in friction and wear behaviour occurs and the equilibrium values of the coefficient f^* of friction and that of the specific wear rate k^* at $T_c > T_{c,f^*}$.

The following is found.

(a) For the materials without glassfibre, in all cases the $\perp$ orientation results in a slightly lower f^* value than is observed for the $\parallel$ orientation. The addition of MoS_2 causes a slight reduction in f^* , *i.e.* from an average value of 0.92 to an average value of 0.85. Adding MoS_2 and graphitic carbon reduces f^* still further, *i.e.* to an average value of 0.59.

(b) For the materials with glassfibre, T_{c,f^*} is somewhat lower for LCP-G-C (approximately 125 °C) than for LCP-G and LCP-G-M (approximately 140 °C). The orientation of the LCP molecules does not seem to affect T_{c,f^*} . The f^* values for LCP-G (0.06 and 0.09 respectively) are distinctly lower than those measured for LCP-G-C (0.10 and 0.18) and LCP-G-M (0.18 and 0.20). This time the orientation of LCPs seems to have a clear effect. The $\perp$ orientation produces a distinctly lower f^* value than the $\parallel$ orientation. The k^* values range from $0.2 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ for LCP-

TABLE 4

Analysis of f vs. T_c and k vs. T_c curves

Material	T_{c,f^*} (°C)	f^*	k^* ($\times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$)
LCP $\perp$	100	0.88	> 10
	100	0.95	> 10
LCP-M $\perp$	120	0.81	> 10
	110	0.88	> 10
LCP-M-C $\perp$	^a	0.58	> 10
	^a	0.60	> 10
LCP-G $\perp$	130	0.06	0.2
	130	0.09	0.3
LCP-G-M $\perp$	140	0.18	1.5
	140	0.21	1.8
LCP-G-C $\perp$	125	0.11	0.7
	125	0.18	0.9

^aNo transition found.

G $\perp$ to $1.8 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ for LCP-G-M ||. According to expectation [11], the k^* values are found to correlate with the f^* values.

4.2. Determination of $p_{\max}$

In the present test series a dramatic increase in wear rate, upon reaching a particular value of p , occurred in all cases, *i.e.* with all materials at sliding speeds of 0.1, 0.5 and 3 m s^{-1} . Thus the wear rate turned out to be the obvious criterion for establishing $p_{\max}$. The results are listed in Table 5.

It can be seen that, once again, the addition of glassfibre is extremely beneficial. On the average, the $p_{\max}$ values increase by a factor of at least 5 if glassfibre is added to the material. Further there are distinct differences between the three glassfibre-containing materials. This time LCP-G-C clearly produces the best results over the whole range of speed values, while LCP-G-M is a relatively poor third. Here it should be pointed out that these results do not agree with the f^* values from Table 3.

4.3. Wear rate determinations at $p = 5 \text{ N mm}^{-2}$ and $v = 0.25 \text{ m s}^{-1}$

Wear rate determinations at $p = 5 \text{ N mm}^{-2}$ and $v = 0.25 \text{ m s}^{-1}$ were performed with LCP-G ||, LCP-G-M $\perp$ and || and LCP-G-C $\perp$ and ||. The steel discs were heated to 150°C , prior to testing. However, in one case (LCP-G-C) a 20°C test was performed as well.

It turned out that in all cases, except when using LCP-G-C at 150°C , extremely severe wear occurred from the very start of the test. On the contrary, LCP-G-C $\perp$ or ||, during the 20 h tested at the 150°C disc temperature, showed a remarkably good friction and wear behaviour. The average coefficient of friction f^* amounted to 0.06 ($\perp$ orientation) or 0.09 (|| orientation) (Fig. 8) and the average specific wear rates k^* were $0.7 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ ($\perp$ orientation) and $0.9 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$ (|| orientation).

TABLE 5
*p*_{max} values

Material	<i>p</i> _{max} (N mm ⁻²)		
	<i>v</i> = 0.1 m s ⁻¹	<i>v</i> = 0.5 m s ⁻¹	<i>v</i> = 3 m s ⁻¹
LCP ⊥	4.3	0.8	< 0.3
	4.3	1.0	< 0.3
LCP-M ⊥	5.4	0.8	< 0.3
	5.4	1.0	< 0.3
LCP-M-C ⊥	6.7	1.2	< 0.3
	6.7	1.0	< 0.3
LCP-G ⊥	^a	^a	^a
	25	10	2.2
LCP-G-M ⊥	27	6.7	0.8
	16	6.7	1.2
LCP-G-C ⊥	26	22	4.3
	40	13	5.4

^aNot determined.

Fig. 9. SEM picture of the worn surface of LCP-G-C. (Original magnification 100×.)

5. Discussion

First, an attempt should be made to explain the remarkable effect of glassfibre on the *f* *vs.* *T_c* and *k* *vs.* *T_c* curves, as shown in Figs. 4–7. This can be done by assuming that, at *T_c* = *T_{c,r}*, appreciable softening of the polymer takes place. According to ref. 14, a first approximation of the coefficient of friction *f* can be found from

$$f = \frac{\tau}{H} \tag{2}$$

In this equation, *τ* represents the interfacial shear strength (systems without adhesive material transfer) or the shear strength of the material of the softer component in

the direct vicinity of the microjunctions which transmit the force (systems with adhesive material transfer). H is the hardness of the softer component.

When testing the materials without glassfibre, the values of both τ and H will be relatively high at $T_c < T_{c,r}$ ("hard polymer"), or relatively low at $T_c > T_{c,r}$ ("soft polymer"). According to eqn. (2) this does not necessarily lead to a reduction in f at $T_c = T_{c,r}$.

However, when testing the materials with glassfibre, a thin film of softened polymer will probably be formed on the surface at $T = T_{c,r}$, leading to a relatively low τ value, while H remains high, because the glassfibres strengthen the matrix of the polymer. According to eqn. (2) this results in a relatively low f value.

The above is corroborated by SEM pictures, taken from worn surfaces of LCPs with glassfibres. As an example, Fig. 9 shows an SEM picture of the worn surface of LCP-G-C. It can be seen that the contact surface is at least partly covered with a thin layer, which can be distinguished clearly from the glassfibre-containing substrate. The fact that addition of MoS_2 or graphitic carbon to glassfibre-containing material causes an appreciable increase in f^* may be because MoS_2 as well as graphitic carbon hinder rather than help the formation of a soft surface layer. The formation of softened surface layers with subsequent shifting of the position of the shear plane from within the polymer to the polymer-metal interface has also been reported for other polymers [15–17].

With regard to the determination of $p_{\max}$, it should be noted first that, at any substantial speed v (say $v > 0.01 \text{ m s}^{-1}$), a sudden drastic increase in wear rate as a result of an increase in pressure p is probably because a critical contact temperature is exceeded rather than to a mechanical effect [18].

In the case of the polymers without glassfibre, such a critical temperature clearly is the temperature at which the wear rate increases drastically, *i.e.* $T_{c,r}$ in Table 4.

On the assumption that a constant specimen mass temperature T_0 is maintained, the contact temperature T_c relates to the total amount Q of frictional heat, which is generated per unit of time and per unit of contact surface as follows:

$$T_c = T_0 + \mathcal{F}(\text{Pé})AQ \quad (3)$$

in which Pé is the Péclet number, in this case given by $\text{Pé} = vd/2\chi$, with d the characteristic measure of the contact surface, χ the thermal diffusivity and A the

Fig. 10. Schematic presentation of temperature T_{d^*} at a depth d^* below the contact surface of the polymer as a function of time t for LCPs with different thermal diffusivities χ . Note that, at 100°C , LCP-G-C has a much higher thermal diffusivity than LCP-G and LCP-G-M (Table 3).

apparent contact surface area [16]. Since Q is given by

$$Q = fvp \quad (4)$$

$p_{\max}$ relates to T_{c,f^*} as follows:

$$p_{\max} = \frac{T_{c,f^*} - T_0}{\mathcal{F}(\text{Pé})Avf} \quad (5)$$

As for these materials the coefficients of friction, directly before transition, are roughly the same (see Fig. 4), the differences in $p_{\max}$ might relate to differences in thermal diffusivity, *i.e.* differences in Pé .

As the filled LCPs, and in particular LCP-M-C, have somewhat higher $p_{\max}$ values than the unfilled material, this would imply that the thermal diffusivity χ of the filled materials is higher than that of the unfilled material. Table 3 shows that this is indeed the case.

In the case of the polymers with glassfibre, an increase in T_c above T_{c,f^*} leads to an appreciable reduction in f , *i.e.* to $f=f^*$ (see Fig. 4). Thus for these materials the drastic increase in wear rate at $p=p_{\max}$ cannot be ascribed to the fact that T_c reaches T_{c,f^*} . Instead thermal collapse of the polymer will probably occur at a T_c value above 300 °C, the maximum temperature in the f vs. T_c curve measurements. Obviously this leads to much higher $p_{\max}$ values than were observed with the polymers without glassfibre.

According to eqn. (5), at constant Pé , $p_{\max}$ values may be expected to be reciprocally proportional to the f^* values, measured for the different materials.

Comparing the results obtained with the materials with LCP molecules, oriented parallel to the contact surface (*i.e.* the $\parallel$ materials), it can be seen in Table 6 that the lower $p_{\max}$ values, found with LCP-G-M, do agree with the higher f^* values, measured with this material. However, LCP-G-C produces distinctly higher $p_{\max}$ values at higher f^* values. This is almost certainly due to the much higher thermal diffusivity of LCP-G-C at higher temperature (see Table 3).

Finally, the wear results obtained with LCP-G-C in 20 h tests at $p=5 \text{ N mm}^{-2}$ and $v=0.25 \text{ m s}^{-1}$ may be explained as follows. As stated above, excellent friction and wear behaviour is found only in tests in which the steel disc is heated to 150 °C, prior to contact with the polymer test piece. This may be because under such conditions the contact surface of the polymer runs in the "safe", *i.e.* the low friction, low wear

TABLE 6
 f^* and $p_{\max}$ values for the glassfibre-containing materials

Material	f^* (Table 4)	$p_{\max}$ (N mm ⁻²) (Table 5)		
		$v=0.1 \text{ m s}^{-1}$	$v=0.5 \text{ m s}^{-1}$	$v=3 \text{ m s}^{-1}$
LCP-G $\perp$	0.06	a	a	a
$\parallel$	0.09	25	10	2.2
LCP-G-M $\perp$	0.18	27	6.7	0.8
$\parallel$	0.20	16	6.7	1.2
LCP-G-C $\perp$	0.10	26	22	4.3
$\parallel$	0.18	40	13	5.4

^aNot determined.

regime, nearly from the very start of the test (*cf.* Fig. 4 and Table 4). On the contrary, at a 20 °C disc temperature the polymer starts running in the high friction, high wear regime, which—under the prevailing severe load and speed conditions—means almost immediate failure.

In principle the other two glassfibre-containing materials, which show a similar f vs. T_c behaviour (*cf.* Fig. 4), might well be expected to perform equally well at a 150 °C disc temperature (be it that their $T_{c,r}$ values are somewhat higher than those of LCP-G-C). However, it should be noted that the formation of a suitable low shear strength layer on the surface, as postulated above, takes some time, if only because the temperature has to reach the critical value $T_{c,r}$ over a substantial depth d^* (say 100 μm) into the material, for enough soft LCP to be formed on the surface, presumably by a mechanism of “thermal extrusion”. It is here that the relatively high thermal diffusivity χ of LCP-G-C becomes a help.

As shown schematically in Fig. 10 for LCP-G and LCP-G-C, with the first material it may—and probably will—take considerably more time for the temperature T_d , at depth d^* below the contact surface, to reach $T_{c,r}$ than with the latter material. This might explain the difference in behaviour.

6. Conclusions

(1) Thermotropic LCPs, based on biphenol chemistry, in unfilled condition or filled with MoS_2 or graphitic carbon, do not qualify as good bearing materials in dry sliding contact with steel.

(2) As long as the contact temperature T_c is below some critical value $T_{c,r}$, of the order of 125–140 °C, the same applies to LCP filled with glassfibre (LCP-G), glassfibre plus MoS_2 (LCP-G-M), or glassfibre plus graphitic carbon (LCP-G-C).

(3) At $T_c > T_{c,r}$, the glassfibre-containing polymers perform very well, with coefficients of friction of the order of 0.06–0.20, depending on the type of material, and specific wear rates ranging from 0.2×10^{-6} to $1.8 \times 10^{-6} \text{ mm}^3 \text{ N}^{-1} \text{ m}^{-1}$.

(4) Also with regard to the load-carrying capacities p_{max} at sliding speeds v of 0.1, 0.5 and 3 m s^{-1} , the glassfibre-containing materials behave much better than the materials without glassfibre. LCP-G-C appears to be the best choice in this respect, owing to its higher thermal diffusivity.

(5) Under severe test conditions ($p = 5 \text{ N mm}^{-2}$ and $v = 0.25 \text{ m s}^{-1}$), only LCP-G-C performs adequately, provided that the test is started at a temperature above $T_{c,r}$. Again this good behaviour may be ascribed to the relatively high thermal diffusivity of this material.

(6) The orientation of the LCP molecules with respect to the direction of sliding (*i.e.* $\perp$ or $\parallel$) does not strongly affect the above results. Obviously, this does not exclude the possibility that orientation of the fibres perpendicular rather than parallel to the contact surface would have a substantial effect.

(7) The above implies that glassfibre-containing LCPs will probably be quite useful at elevated temperatures. At temperatures below $T_{c,r}$, the materials should preferably not be exposed to sliding contact with steel. If this cannot be avoided, such contact should be as brief as possible and it should take place under mild conditions, *e.g.* at $R_a \leq 0.1 \mu\text{m}$ centre-line average, $p \leq 1.0 \text{ N mm}^{-2}$ and $v \leq 0.1 \text{ m s}^{-1}$ (*cf.* Figs. 6 and 7).

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