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Dry self-lubricating composites

Shin Jen Shiao and Te Zei Wang
National Chiao Tung University, Institute of Applied Chemistry, 1001 Ta Hsue Road, Hsinchu, Taiwan 300, ROC
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Chopped strand carbon fibers, glass fibers and their hybrids were used to reinforce an epoxy matrix to which additives of PTFE, graphite and molybdenum disulfide were used for producing a dry self-lubricating material. Their tribology properties were studied using testing machines of thrust and journal radial. Also, the *PV* value, friction coefficient, wear rate and the contact surface temperatures were determined. The compression strength of the bush ring and the impact strength of material were evaluated. The surfaces of wear were investigated. The mode of fracture mechanism is proposed according to the specimens morphology. The relationship between friction coefficient and loading correlated well with the Myoshis equation in the case of a backing material. This study provided an optimal approach of making dry wear bearings by glass fibers backing at low friction coefficient. Copyright © 1996 Elsevier Science Limited

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INTRODUCTION

The friction coefficient of a polymer has low tribology properties that have been recently used as the parts of bearing, gear and oil sealing. In addition to the polymer matrix having self-lubrication properties, its mechanical property meets the requirement of a bearing. The vibration absorbing property is better than that of metallic systems[1–3]. Poor mechanical strength, low thermal conductivity and great thermal expansion are limitations of the polymeric bearing. However, the application of reinforcement in composites can compensate for these weaknesses. Moreover, the glass fibers and carbon fibers are the most highly promising reinforcement materials in the composites. The former can improve the wear of polymeric material, the *PV* value (value of load multiplied by rubbing velocity of a bearing)[4], impact strength, thermal conductivity and thermal strain; however, it can increase the wear of the antibody. The latter, however, can increase the thermal conductivity, decrease the friction coefficient and then increase the *PV* value. However, a high cost and the small fracture strain are its disadvantages. Combining the use of carbon fibers with glass fibers in an epoxy matrix will incorporate the advantages of these fibers and subsequently lower the cost. Homogeneous hybrids for the types of fiber arrangements have been investigated extensively[5]. Our previous work examined the effects that solid lubricants have on the tribology property[6]. Our later work investigated the self-lubricating bearing system of the glass fiber/carbon fiber/epoxy system by the filament method[7]. This study explored the use of chopped carbon fibers as the inner layer reinforcement, backed with glass cloth or a glass mat in the outer layer in a high rate. Some additives, such as PTFE and molybdenum disulfide, in an epoxy matrix are also used in order to increase the yield strength, elastic modulus and tribology property of the composites. Moreover, the relationships between friction coefficient, specific wear and the change of mechanical strength are discussed. A method of hybrid type for the epoxy system is also developed.

EXPERIMENTAL

The materials used in this experiment were EPON 828 matrix from Shell Co., the curing agent of BF_3MEA from Takeda Co., the 3 mm chopped strand glass fibers of AGM-450 from Dalai Co., the chopped carbon fibers were also 3 mm of Tairyfil CO6K33 from Taiwan Plastic Co. and graphite, MoS_2 and PTFE from Takeda Co. The compositions were 10 phr of curing agent mixed at 90°C and the additives were combined in the range of 10–20 phr, then with fibers and formed a prepreg of size 14 cm × 8 cm × 0.5 cm. Following storage in frozen box for 30 min, the prepreg was set in a mold of size ø 5 cm × ø 4 cm × 3 cm at the conditions of 100°C and 5 mmHg vacuum in an oven for 50 min and then the temperature was increased to 140°C for 30 min and the pressure to 80 kg/cm^2 and then to 100 kg/cm^2 for 60 min. Finally, after molding, a post treatment was performed in an oven at 165°C. The ring strength was tested using an Instron at a cross-head rate of 10 mm/min. The friction coefficients of the bearings were tested using a Thrust testing machine and a Journal testing machine. The testing conditions were selected at a constant rotational speed and the load was changed after a time interval of 10 min; otherwise a constant load was selected and the rotational speed also changed after 10 min. The testing for endurance strength was also performed at the condition of taking the value of one-third of the *PV* value. For all the tests the surfaces of the counter body were cleaned with acetone and the specimen temperature was recorded.

RESULTS AND DISCUSSIONS

Hybrid fracture mode

The impact strengths are summarized in *Table 1*. The fracture surfaces of impact were observed in a scanning electron microscope (SEM). The epoxy resin is well known to be a rather brittle property and their fractures are brittle-fracture. When reinforced with carbon fibers, the fracture is more likely to have the same properties as the matrix. However, when reinforced with glass fibers with a high impact strength, the fracture mode changed to a tough-type. The reinforced composites with glass mat and glass chopped strands show a fracture of slow propagation. When reinforced with glass cloth, the fracture is a hybrid mode of slow propagation and multi-shearing. In addition to the energy required to break the woven fibers, the delamination fracture also has the same characteristic that did not appear in the cases of composites made of a glass mat and chopped glass fibers.

A comparison of impact strengths obtained from both experimental and mixed-rule revealed that the largest difference between theoretical and testing values is about 9% and an average of 3–5%, summarized in *Table 2*. Such an estimate is sufficient to obtain the impact strength of composite hybrid with carbon fibers and glass fibers by directly calculating the mixed-rule.

Table 1 Impact strength

Specimen	Impact strength kg·cm/cm	Specimen	Impact strength kg·cm/cm
Epoxy	2.39	22.5C7.5G	53.71
20C	7.93	15C15G	92.30
30C	12.13	7.5C22.5G	138.22
40C	18.92	3.75C26.25G	138.22
30G	172.13	7.5C22.5m	54.82
30m	54.82	11.25G22.5m	46.39
30S	76.88	3C27S	67.95
30C5P	11.11	6C24S	61.87
30C10P	16.65	9C21S	52.26
30C15P	14.75	30C15PB30m	48.48
30C20P	10.18	30C15PB40m	75.47
30C5m	15.17	30C15PB50m	106.98
30C10m	13.24	30C15PB30G	173.58
30C15m	13.68	30C15PB40G	190.77
30C20m	13.00	30C15PB50G	210.00
30C25m	13.95	30C15PB60G	268.87

Table 2 Comparison of experimental impact strength with theoretical value for hybrid, in kg × cm/cm

Glass fiber	Carbon fiber	Vg : Vc	Experimental value	Theoretical value	Error %
Cloth	Chop strand	1:3	52.6	52.1	+0.90
		1:1	92.3	92.1	+0.19
		3:1	138.2	132.13	+4.6
Chop strand	Chop strand	7:3	52.26	57.45	−9.02
		8:2	61.87	63.93	−3.22
		9:1	67.95	70.40	−3.48

Table 3 Ring compressive strength

Specimen	Maximum loading kg/cm^2	Yield psi × 10^3	Modulus psi × 10^3
Epoxy	35.8	35.8	1.7
20C	52.3	—	
30C	71.2	66.7	5.6
40C	91.5	84.4	7.3
30G	119.5	119.2	6.2
15C15G	107.0	68.4	6.2
15C15S	62.9	—	—
22.5C7.5G	80.9	—	—
7.5C22.5G	110.2	—	—
15C15G5P	106.6	—	—
15C15G10P	110.3	—	—
15C15G15P	99.3	73.8	6.0
30C10P	70.2	61.0	5.6
30C15P	68.0	57.5	5.1
30C20P	70.5	50.5	5.5

Ring compression strength

The values of compressive strength, strength of yield point and modulus of specimens are summarized in *Table 3*. In the carbon fiber reinforced resin in which PTFE was added (such as 70.2 kg/cm^2 (10 phr), 68 kg/cm^2 (15 phr) and 70.5 kg/cm^2 (30 phr)) the PTFE amounts do not have much affect on the maximum compressive strength. However, the PTFE additive decreases the yield strength. The PTFE can obviously not only decrease the shear strength and friction coefficient of the material, but also increase the friction coefficient of material by lowering the yield strength. Also, total effects caused by both shear strength and yield strength during the addition of solid lubricant must be considered. The compressive strength and elongation are always coincidental when the reinforcement is with fibers[2]. The yield strength of compression and its elastic modulus directly affect the contact surfaces of friction condition and then affect the friction coefficient. From the Tsukizoe relationship[5], more yield strength implies less contact area. Moreover, the elastic modulus is also one of the varieties of wearing amount. Also, higher elastic modulus implies lower wearing amount.

Theoretical discussion and analysis of the experimental results reveal the optimal condition for PTFE addition is 15 phr. On the basis of this data, the composition for formulating the inner layer of bearing is taken here. Next, a high volume rate of glass cloth or glass mat for reinforcement in the outer layer of bearing is used to gain an increased yield strength and elastic modulus. Finally, the friction coefficient reduces at the same condition of surface shearing.

The values of ring compressive strength for bearings backed with glass fibers, yield strength and modulus are summarized in *Table 4*. The yield strength increases with an increase in the glass cloth in the composite to a maximum of 160.3 kg/cm^2 at a rate of 60% reinforcement, that is 2.5 times the sample not backed with glass cloth. The rigidity is equal to that of glass. However, the maximum strength falls between the strength of glass cloth and carbon fibers; it is also higher than the theoretical value calculated from mixed-rule at the conditions in which $v_f = 0.3$ and the hybrid ratio of glass cloth and carbon fibers is 1 : 1. During the compression testing, the load was borne on the outer layer of glass cloth, thereby making the elastic modulus of the hybrid equal to the strength value of a pure glass cloth. The load propagated from the outer to the inner; the carbon fibers began to yield when it reached the strength of carbon fibers. Under the condition of glass cloth backing, the carbon fibers will yield a much larger strain. The Phillips fracture growing theory states that, at the moment of fracture of carbon fibers, the glass fibers stop the propagation of fracture line and the carbon fibers can still bear a part of the load[8].

The reinforcement of glass cloth for brittle epoxy resin can gain a higher fracture strain and higher toughness than those of carbon fibers. The toughness of backing with 60% glass fibers reaches 105.1 in-#/in^3, i.e. 5.5 times higher than that of 19.0 in-#/in^3 having no backing.

Friction coefficient

The friction coefficient of pure epoxy increases with an increase in loading and reaches a maximum value of 0.6. The matrix would soften at the surface on higher loading. This occurrence correlates with the theory proposed by Shimbo[9]. The friction property of composites reinforced with carbon fibers, lower than 30%, would not be comparable with the matrix. Lancaster[8], who studied various plastics reinforced with chopped carbon fibers, introduced two reasons to elucidate the lower friction coefficient are: (1) the carbon fibers up to the surface of friction surface and supports some part of loading, and (2) the smoothness of carbon fibers reduce the strain of contact point at some area.

The *PV* value of pure epoxy resin is 87.9 (kgf·m)/(cm^2·min). After adding carbon fibers, the *PV* value increases with the volume of carbon fibers. Those values are $PV = 199.3$ ($V_f = 0.2$), $PV = 281.2$ ($V_f = 0.3$) and $PV = 246.1$ ($V_f = 0.4$). The maximum value of effect loading on the friction coefficient μ is greater than that of pure epoxy resin as shown in *Figure 1*. Ramesh[10] explained that carbon fibers increase the contact surface of the solid that induced the increase in μ value.

Adding solid lubricant is an attempt to lower the μ value. Under the condition of a perfect covering of a solid lubricant on the entire friction surface, the actual contact area is determined by hardness of the matrix.

Table 4 Ring compressive strength for bearing backed with glass fiber

Specimen	Maximum load kg/cm^2	Yield strength psi × 10^3	Modulus psi × 10^3
30C15PB30M	130.5	126.7	6.5
30C15PB40M	143.1	137.7	7.3
30C15PB50M	159.0	149.0	8.3
30C15PB30G	110.1	96.7	6.1
30C15PB40G	135.3	117.1	7.1
30C15PB50G	151.9	151.3	9.1
30C15PB60G	160.3	160.2	10.6
30C15P	68.0	57.5	5.1

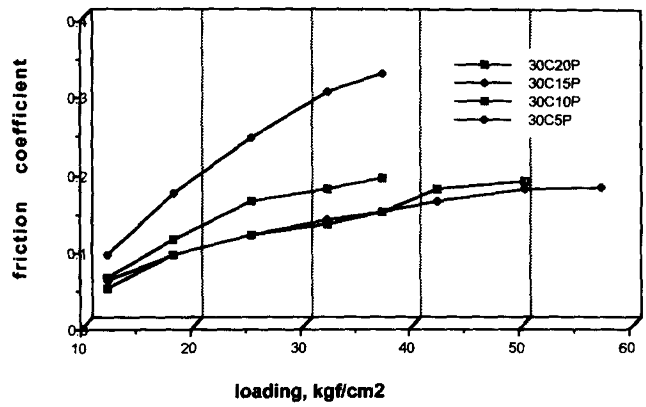

Figure 1 Relationship between friction coefficient and loading at various amount of PTFE, sliding velocity 3.77 m/min

When the shearing occurs on the surface, the small shear strength of the solid lubricant would suffer and a low μ value would be produced. Moreover, the tribology film formed by the solid lubricant would make the surface much smoother. This lowers the local strain at the contact point and subsequently increases the *PV* value. The lubrication film also reduces the material wear.

The maximum μ value of a bush bearing containing PTFE is about 0.10, i.e. only a half-value of the one without PTFE. The μ value decreases with an increase in PTFE content to about 15% and further increases with an increase in loading. With the addition of MoS_2, on different amounts and for different loading conditions, the μ value decreases at a load above 22.5 kg/cm^2, especially with the additions of 10 and 15 phr. At 25 kg/cm^2, the μ value drops from 0.45 to 0.3 when the specimen temperatures were 61°C and 57°C, respectively. The decrease in μ value may be elucidated by the vaporization of surface moisture. That is a low bonding between S– and –S face, the moisture can increase this bonding and the removal of moisture decreases the bonding strength resulting in a small value of μ.

For the optimum condition of MoS_2 in tribology, the MoS_2 containing material should be: (a) used in a moisture free atmosphere; (b) where the temperature is around 80–100°C.

A relationship between the hybrid of carbon fibers and glass fibers that the μ value of an epoxy resin was postulated by Bowers and Zisman[11] can be expressed as

$$\frac{1}{\mu} + V_c\frac{1}{\mu_c} + V_m\frac{1}{\mu_m} + V_g\frac{1}{\mu_g} \qquad (1)$$

where V is volume fraction, m is matrix, c is carbon fiber and g is glass fiber. A composite reinforced with carbon fibers and backed with glass fibers has a higher μ value than the one reinforced with only carbon fibers. How to obtain an improvement of lubrication, mechanical strength and lower cost by selection of proper hybrid are the purposes of this study.

The concept of Bowers and Zisman was also applied to bearing[11]. From a soft metallic film coated on a surface of hard metal, for example, a low shear strength is obtained from the film and a high yield strength is obtained from the hard substrate. Applying this design concept, coating a layer of high lubricant material on a harder backing surface, the friction coefficient is as follows:

$$\mu = \mu_f \frac{\tau_f}{P_m} \quad (2)$$

where τ_f is the shear strength of a soft film and P_m is the yield strength of a hard backing material.

The μ value of film is

$$\mu = \mu_f \frac{\tau_f}{P_f} \quad (3)$$

where P_f is the yield load of film. Combining equation (2) with equation (3) yields

$$\mu = \mu_f \frac{P_f}{P_m} \quad (4)$$

Equation (4) shows that the increase of P_m in a low μ value can be expected. Under the condition of a very small ratio value of P_f/P_m, the error would be very large[12]. Regarding the same design concept, this study using a film of low μ value composition of 30% carbon fibers +15% PTFE, with the maximum μ value of 0.17 and the high strength backing is 40–60% glass fibers. Consequently, a low shear strength in the fibers and high yield strength in the glass layer can be obtained. Increasing the glass fiber content in backing layer correspondingly increases the yield strength. The yield strength of 50% glass fibers backing is 151.3 kg/cm^2 and increases to 160.2 kg/cm^2 when the glass fibers increase to 60%. In this study, the workability limit of glass fiber content is 60%. A reflection point shows in the curve of backing 50–60%. These phenomena were also found for the modulus. This is caused by the wetting effect between the glass fibers and epoxy resin.

Under different volume fractions, the relationship between loading and μ value for backing with glass cloths and mats are shown in *Figures 2* and *3*, respectively. The μ value dropped from the maximum of 0.17 to 0.08, even when the loading is greater than 100 kg/cm^2. According to the results in *Figure 2*, we can expect that the μ value would decrease if the loading is significantly less than 100 kg/cm^2. A testing condition of constant loading at 5 kg/cm^2 was carried out for specimens 30C15P and 30C15B60G. The results of relationship between friction coefficient and sliding velocity are shown in *Figure 3*. The specimen backed with 60% of

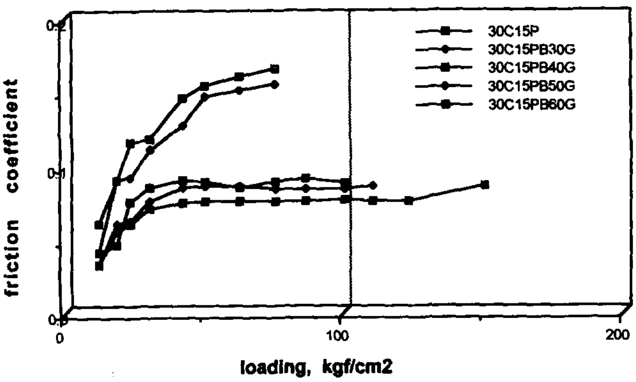

Figure 2 Relationship between friction coefficient and loading for bearing backed with glass cloth, sliding velocity 3.77 m/min

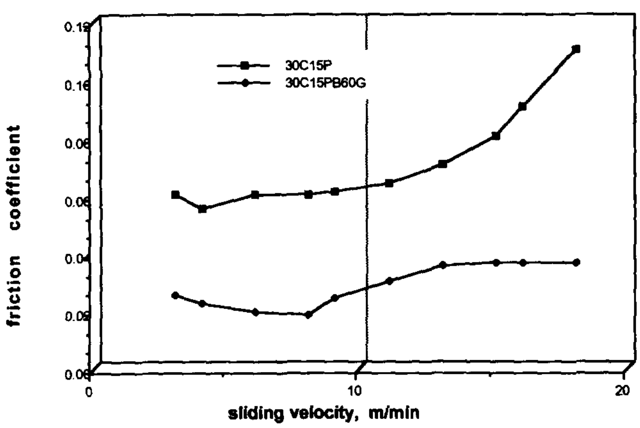

Figure 3 Relationship between friction coefficient and sliding velocity for specimens 30C15P and 30C15PB60G at loading of 5 kg/cm^2

glass cloth shows an almost constant μ value ranging between 0.02 and 0.03. Meanwhile, the specimen without a backing of glass cloth shows an increasing μ value from 0.06 up to greater than 0.1.

The effects of sliding on the plastics are considered next concerning (a) increasing the contacts during the relaxation in the micro unit of time and (b) the effect of strain speed on the strain reluctance. Generally, the μ value of plastics increases with the sliding speed. However, under a high speed condition, the phase change of plastic surface is similar to the contact of an elastic body, in which the μ values decrease with an increase in speed.

The friction force increases with the high speed for high melting viscosity of high melting materials. The reason only PTFE is suitable in the conditions of high loading and low sliding speed is that the temperature of the sliding surface of PTFE increases when the sliding speed increased. Moreover, the molten state viscosity is 10^{11}–10^{12} poise[12] and has a very large strain force for PTFE.

The relationship between temperature and μ value of specimen made of 30% carbon fibers +15 phr PTFE and backing with 60% glass fibers at the condition of 5 kg/cm^2 is shown in *Figure 4*. When the temperature remains constant at 25°C, the μ value decreases with an increase in sliding velocity and then drops from 0.025 to

0.015 at the condition of 7.5 m/min. Both temperature and μ value increase gradually at a velocity higher than 10 m/min and the μ value becomes a constant value of 0.035. The primary advantage of backing with glass fibers is to increase the elastic property of material and obtain an elastic contact at high speed operation, thereby decreasing the contact area and lowering the μ value.

Wear

Although the mechanism of wear for fiber reinforced epoxy resin correlates with the theory of delamination postulated by Suh[13], the plastic strain on such a substrate to cause a shear would be resisted by the addition of fibers.

During the forming of debondings, the crack grows between fibers and the matrix easily.

From inspection of the wear surface, the wear crushes of epoxy resin are delaminated from the surface. That is, the phenomena identified as delaminations wear. There are debondings of fibers from matrix and the broken fibers on the wear surface. The addition of PTFE decreases the delamination phenomena and reduces the wearing. Also, backing the specimens with 60% glass cloth reduces the occurrence of delamination. The destroying procedure of the structure is that, before the matrix layer is taken away from the surface, the interface of fibers and matrix is destroyed first. Next, the fracture segment broke and detached and finally the μ value rose. This mode is different from the pure epoxy resin debonding and causes an increase in the value of μ.

From the observation and discussion regarding the wear surface, we postulated a mechanism of fiber reinforced epoxy as follows:

(1) The matrix and fibers were worn thin by the steel shaft.
(2) Debonding between the interface of fibers and matrix.
(3) Finally, the fibers broke, detached and the matrix was removed by lamination.

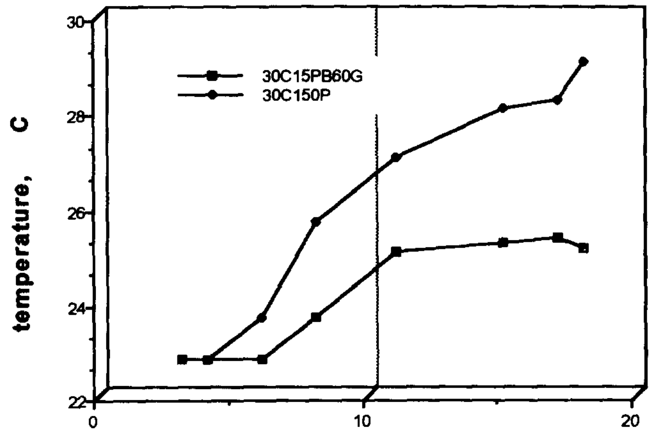

Figure 4 Relationship between surface temperature and sliding velocity for 30C15P and 30C15PB60G at loading of 5 kg/cm^2

The mechanism described above is affected by three factors: (1) wearing affected by loading W and sliding distance D, (2) the fibers broken were affected by the strain amount ($\mu P/E$), loading and distance of sliding, and (3) delamination was affected by shear force of the layer, stress amount, loading and distance of sliding.

The wear volume Q during friction can be expressed as follows[5]:

$$Q = K\frac{\mu P}{E} \times \frac{1}{I_s} DW \tag{5}$$

where I_s is the interlaminar shear strength of the composites and K is a constant. The wear rate W_s is

$$W_s = K\frac{\mu P}{E} \times \frac{1}{I_s} \tag{6}$$

Under a constant loading, plotting W_s against $\mu P/E$ and analyzing the data, equation (7) can be obtained.

$$W_s = 1.4 \times 10^{10}\left(\frac{\mu P}{E}\right)^{3.08} \times \frac{1}{I_s} \tag{7}$$

By applying high strength, high modulus glass fibers as a backing material, a low μ value can be obtained. From the wear equation we know a material with low wear rate would have a low μ value. Moreover, due to backing which introduces a high elastic modulus, this term causes a low wear rate. Therefore, the design of this study is very good to lower both μ and wear. Under the same conditions of load and friction interface, the same shear strength can be obtained. However, the effect of backing composites can decrease the μ value, increase elastic modulus and finally decrease the wear quantity.

The PV testing values of 30% carbon fibers +15% phr PTFE and backing with 60% glass cloth are shown in *Figure 5*. Evidently, the limited value can be raised markedly by the backing method. Some resistance testings and wear testings of specimens are summarized in *Table 5*. Their steady μ values exhibit an adequate tribology property. Taking specimens of 15C10P15G and 15C9P6g15G for example, their μ values are about 0.04. A comparison of their results reveals that the latter has a more steady μ value and temperature curves than the former because of the addition of graphite. The reason is that the graphite has a high thermal conductance coefficient that made the heat dissipate quickly from the contact surface and obtained a steady friction film. Their data are $\mu = 0.65$–0.09 and $W_s = 1.6 \times 10^{-6}$ mm^3/(kgf·m) for the non-graphite-content one, and $\mu = 0.02$–0.092 and $W_s = 7.5 \times 10^{-7}$ mm^3/(kgf·m) for the graphite containing one. Even though the addition of graphite increases the μ value, this made the shear strength and elastic modulus greater, thereby reducing the wear quantity.

The bearing property of products developed by this study has a specific wear rate of 7.2×10^{-7} mm^3/(kgf·m) and PV value of 560. These rates imply good characteristics and satisfy the requirement of commercial needs. That is, the PV value of commercial nylon composites is 300–400, and 300–500 for polyurethane composite materials.

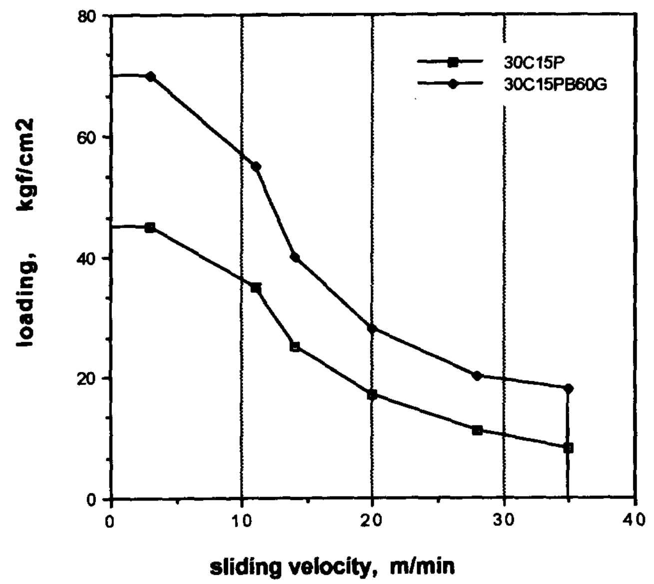

Figure 5 *PV* curves for 30C15P and 30C15PB60G

Table 5 Analysis results from equation of specific wear rate

Testing mode	Specimen	$(\mu P/E)^{3.08}$	W_s
Thrust	30C15PB60G	2.91×10^{-12}	2.98×10^{-6}
Thrust	30C15PB50m	2.24×10^{-12}	1.61×10^{-6}
Journal	30C15PB60G	1.08×10^{-12}	7.20×10^{-7}
Journal	15C10PB15G	1.46×10^{-12}	1.00×10^{-6}

Table 6 Data obtained from equation $\mu = KW^n$

Velocity, m/min	3.77		5.56		7.54	
k and *n* values	$k \times 10^{-3}$	n	$k \times 10^{-3}$	n	$k \times 10^{-3}$	n
30C15P	6.371	0.456	6.254	0.452	—	—
30C15PB30G	6.373	0.453	6.094	0.453	—	—
30C15PB40G	4.719	0.418	5.653	0.444	2.700	0.43
30C15PB50G	4.418	0.409	5.690	0.441	5.685	0.43
30C15PB60G	3.360	0.375	3.027	0.372	3.530	0.38

Loading characteristics

Under some conditions the ceramics, such as MgO, Al_2O_3, and SiC show the phenomena of elastic fluiding[14]. Donald studied silicon carbide ceramic material, and the relaxation between μ value and loading w, indicated that, in the field of $1.4\text{–}3.0 \times 10^4$ N/mm^2, the μ value increases with the increase of loading. The relationship is expressed as

$$\mu = KW^{0.3-0.4} \quad (8)$$

The authors studied the brittle epoxy resin and the addition of carbon fibers to form a hard and brittle friction surface, which is somewhat similar to the property of ceramics.

Applying the equation (8) to analyze the products backing with/or without glass fibers, the values of k and n are summarized in *Table 6*. The values of n in $\mu = KW^n$ are 0.35–0.40. These are very close to that of Miyoshi's analyzed value for ceramics[15].

The larger increase in the stiffness causes a closer approach to $n = 0.3$–0.4. At the backing with 60% glass cloth, the n value falls in that range. Moreover, when increasing the glass cloth content, the μ value increases with the increase of loading; however, the rates are reached much more moderately. This is because a high fiber content caused a high strength and high stiffness. When at the same loading condition, the strain quantity would be reduced and a small μ value subsequently obtained.

CONCLUSIONS

The following conclusions can be made on the basis of the above discussion:

(1) The impact strength of hybrid made from carbon fibers and glass fibers obeys the mixed-rule, while the ring compressing strength shows the positive hybrid effect.
(2) The material backed with glass fibers could reduce the μ value to as low as 0.02 at a rate of backing with glass cloth of 60%, the wear rate to 7.2×10^{-7} mm^2/(kgf·m), and increases to a *PV* value of 560 (kgf·m)/cm^2·min).
(3) The wear mechanism of carbon fiber reinforced material is wearing the surface thin first, then debonding the fiber and matrix and finally breaking and delaminating.
(4) The relationship of μ value and loading for composites backing with glass fibers is $\mu = KW^n$, where $n = 0.35$–0.41.

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