

Tribological performances of fabric self-lubricating liner with different weft densities under severe working conditions

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Several woven fabric self-lubricating liners with weft densities of 200-450 root/10cm in a spacing of 50 root/10cm have been prepared to investigate the tribological performances of the liner under severe working conditions, such as low velocity and heavy load (110, 179 and 248 MPa) and high velocity and light load (9, 18 and 27 m/min) by utilizing the self-lubricating liner performance assessment tester, and MMU-5G friction and wear tester respectively. The worn surface is characterized using confocal laser scanning microscopy. The tribological results show that the fabric self-lubricating liners with different weft densities share almost the same tribological property variation tendency. Fabric tightness affects the wear rate and the stability of wear resistance of liners under severe working conditions. The overall level of friction coefficient and the wear rate of liners with different weft densities are influenced by the cold flow degree of the polymer. In addition, proper weft density improves the tribological properties of liner and a preferred weft density for the liner under severe working conditions is found to be 300–350 root/10cm.

Keywords: Fabric self-lubricating liner, Kevlar, Polytetrafluoroethylene, Tribological performance, Weft density

1 Introduction

Self-lubricating spherical plain bearing has been widely used in various fields, such as engineering machinery, water conservancy facilities, military industrial machinery, automobile, aerospace and high-speed rail¹. The service life of the self-lubricating spherical plain bearing much depends on the tribological properties of the fabric self-lubricating liner bonded to the inner face of outer ring.

Excessive wear of the liner material could result in failure of the bearing. Normally, the fabric self-lubricating liner is a kind of woven composite which consists of polytetrafluoroethylene (PTFE) and Kevlar/reinforced fibre and other fillers. PTFE is a kind of perfect self-lubricating material owing to its low friction coefficient and good high temperature and chemical stability. However, PTFE cannot be used as anti-wear material solely because of its poor mechanical properties, low thermal conductivity and anti-wear properties. In order to improve its anti-wear properties, inorganic or organic fillers such as glass and carbon fibre are usually used to reinforce the PTFE²⁻⁵. Hence, the modified PTFE-based composites have been applied as self-lubricating materials in many fields. Among these, woven composites with

fabric as matrix, which is coated on the metal surface using adhesive resin, have been considered as an excellent bearing liner for tribological applications. Many characteristics such as good self-lubricating, wear resistance, load-carrying capacity, as well as low density, have made the fabric composites popular as compared to conventional composites⁶. Many researchers have studied the mechanical performance, tribological property and thermal conductivity of PTFE and its composites under various conditions, such as dry sliding condition⁷⁻⁹, static load conditions¹⁰, sea water¹¹ and oil-less compressor condition¹².

The fabric, as the matrix of the fabric self-lubricating liner, performs the functions of bearing load and provides self-lubricating material, which have a very significant effect on the mechanical behavior, friction and wear properties of the liner. Technically, the weaving parameters are found critical with many properties of the fabric¹³. Studies showed that the weft density affects the skewness, the free spaces between the floats, the float length and the shearing rigidity of the fabric¹⁴. Also, the fabrics woven with thicker weft yarns at higher weft densities exhibited higher bending rigidities and drape coefficients¹⁵. The effects of woven linear density on the properties of composites made of E-glass fibre and epoxy systems have also been investigated¹⁶. Akgun *et al.*¹⁷ studied the effect of fabric constructional parameters on percentage

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reflectance and surface roughness of polyester fabrics, which indicated that the weave pattern, weft density and yarn floats play important roles on percentage reflectance and surface roughness of the polyester fabrics. However, the tribological performances of the fabric self-lubricating liners with different weft densities are rarely reported.

Therefore, in this study, several fabric self-lubricating liners, woven with PTFE and Kevlar fibres with different weft densities, have been prepared to investigate their tribological performances under severe working conditions in order to obtain a better weft density range and to improve the friction and wear properties of the fabric self-lubricating liner.

2 Materials and Methods

2.1 Fabrication of Self-lubricating Liner

Fabric having 1/3 cross-twill structure was woven on Y200S electronic sample loom (NanTong SanSi Electromechanical Science & Technology Co. Ltd., China) and used for fabrication of the liners. The

woven fabric was soaked in acetone for 24 h, and then boiled for 15 min in distilled water. After drying in the oven at 80°C for 1 h, the fabric was soaked in phenolic-acetal resin and cleaned by ultrasonic cleaning oscillation for 3 h. In order to make the fabric fully saturated with resin, a glass rod was used to roll on the liner and to ensure that there were no bubbles on the fabric surface. Finally the fabric would be dried in the drying oven at 110°C for 1 h. Figure 1 shows the micrographs of dipped self-lubricating liners using the confocal laser scanning microscopy (CLSM, OLYMPUS, OLS3100, Japan).

The PTFE fibre used in weft direction was supplied by Shanghai Lingqiao Environment Protecting Equipment Works Co. Ltd., China, manufactured with thin-film cutting technology. The aramid fibre (Kevlar#49) used in warp direction was supplied by DuPont, USA. The modified phenolic resin was supplied by Shanghai Xinguang Chemical Co., Ltd., China. Properties of the two fibres and the resin are listed in Table 1.

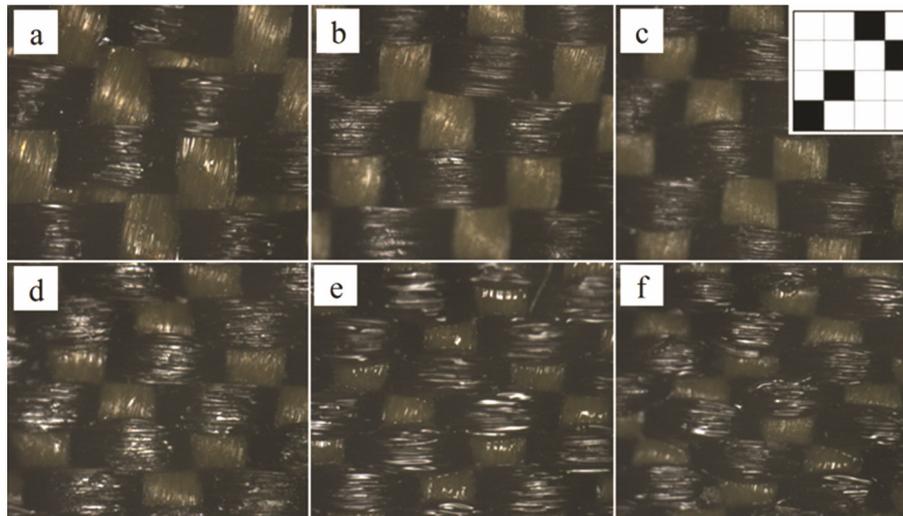


Fig. 1—CSLM micrographs of dipped fabric self-lubricating liners with different weft densities [(a) 200 root/10cm, (b) 250 root/10cm, (c) 300 root/10cm, (d) 350 root/10cm, (e) 400 root/10cm, and (f) 450 root/10cm (warp density 290 root/10cm)]

Table 1—Physical characteristics of PTFE, Kevlar 49 fibres and resin

Type	Liner density, dtex	Density, g.cm ⁻³	Tensile strength, cN/dtex	Shrinkage factor, %	Working temp., °C
PTFE	400	2.0	>0.7	<2	-190-260
Kevlar 49	400	1.45	215	3.3	-196-204
Resin	Working temp., °C	-70 -200 °C			
	Shear strength, MPa	≥15 (room temp.)			
	Curing temp., °C	180			
	Curing pressure, MPa	0.1~0.2			
	Curing time, h	2			

2.2 Tribological Tests

2.2.1 Under Low Velocity and Heavy Load Condition

Sliding friction experiments under low velocity and heavy load condition were carried out under laboratory conditions using the self-lubricating liner performance assessment tester. Figure 2(a) shows the schematic diagram of the tester. The experimental parameters are listed in Table 2.

The wear loss of the liner in the experiment can be measured online through the self-lubricating liner performance assessment tester and the friction coefficient (μ) and wear rate (K) can be obtained using the following equations.

$$\mu = \frac{M}{DF} \quad \dots (1)$$

$$K = \frac{h}{PN} \quad \dots (2)$$

where M is the friction torque (N·mm); D , the diameter of the central spindle (mm); F , the load (N), P , applied pressure (MPa), h , the wear loss (mm); and N , the cycle times (s). Each experiment was repeated three times to ensure the reliability and accuracy of the data.

2.2.2 Under High Velocity and Light Load Condition

Sliding friction experiments under high velocity and light load condition were carried out under laboratory conditions using the MMU-5G friction and wear tester. Figure 2(b) shows schematic representation of the MMU-5G tester. The experimental parameters are listed in Table 2.

The variation in friction coefficient with time can be supervised online through the MMU-5G friction and wear tester, and the friction coefficient curve can be obtained directly as soon as the test is finished. Wear depth (h) can be measured, and the wear rate (K) and wear volume (V) can be obtained using the following equations.

$$K = \frac{V}{FL} \quad \dots (3)$$

$$V = h \cdot s \quad \dots (4)$$

where V is the wear volume (m³); F , the load (N); L , the sliding distance (m); h , the wear depth (m); and s , the wear area (m²). Each experiment was repeated three times to ensure the reliability and accuracy of the data.

3 Results and Discussion

3.1 Friction Coefficient

Friction coefficients of the fabric self-lubricating liners with different weft densities under severe working conditions are given in Fig. 3; the values are average ones obtained at stable friction stage.

Friction coefficients of fabric self-lubricating liners with different weft densities under both working conditions decrease with increasing load/velocity. It can be observed that the friction coefficients of the fabric liners with weft density of 300–350 root/10cm are lower than liners with other weft densities under both working conditions. Fabric self-lubricating liners

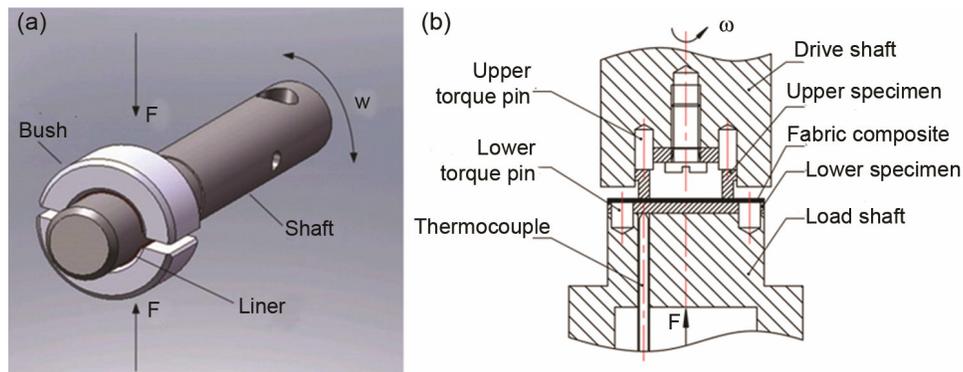


Fig. 2—Schematic representation of (a) motion diagram of self-lubricating liner performance assessment tester, and (b) MMU-5G tester

Table 2—Friction and wear experimental parameters under low/high velocity heavy/light load condition

Working condition	Load, MPa	Oscillation frequency/speed	Oscillation angle, deg	Time, h	Environment temp., °C
Low velocity heavy load	110, 179, 248	12 Hz	± (25±5)	20	Room temp.
High velocity light load	10	9, 18, 27 m/min	—	2	Room temp.

with low weft densities cannot provide enough lubricating material (PTFE film) and hence the friction coefficient increases. For fabric liners with high weft densities, the fabric planeness of the liner is negatively influenced, and the relative content of the Kevlar fibre which possesses low antifriction property is turned higher. In this case, the friction coefficient of the fabric liner also increases. It is observed from Figure 3(a) that the values of friction coefficient of the fabric liners with different weft densities at each load are different; the values fluctuate in a small range. These phenomena indicate that the weft density affects the friction coefficient to a certain extent but it does not change the variation tendency of friction coefficient. To explain the variation tendency of the friction coefficient with load microscopically, the increasing load reduces the intermolecular cohesion, which would cause a decrease in friction coefficient. Macroscopically, as load increases, the actual contact

area of friction surface increases. Plastic deformation occurs on part having PTFE fibre under combined action of high normal stress and friction shear stress. Some PTFE fibres are worn down to become wear debris and filled in valley of the liner to play an inlaid lubricating role in the stable friction stage, which could reduce the friction coefficient significantly.

Figure 3(b) shows that the friction coefficients under high velocity and light load condition show variation in trend similar to that under low velocity and heavy load condition and a higher overall level. In fact, a quantity of friction heat is generated on friction interface and the contact time of the contact points could be shortened while friction velocity is increased. In the meantime, the diffusion of friction heat generated in instant time is delayed and hence the heat is gathered on the friction surface. Besides, due to the poor thermal conductivity, extremely high flash temperature generates on microns area, which results in the fabric self-lubricating liner suffering a drastic friction interface temperature rise (Fig. 4). Moreover, since the liner is viscoelastic, higher heat increases the visco-elasticity of the PTFE fibre, which makes the material soft, accelerates the plastic deformation and decreases the shear resistance. High temperature can lead to the increase in creep degree of the PTFE fibre¹⁸, which decreases the attraction between PTFE molecules in the PTFE fibre. Beneficially, these changes result in material adhesion and transfer to form more lubricating film. In summary, high friction temperature caused by the increased velocity is greatly helpful in the formation of lubricating film which could greatly improve the lubricating state of the self-lubricating liner and decrease friction coefficient directly.

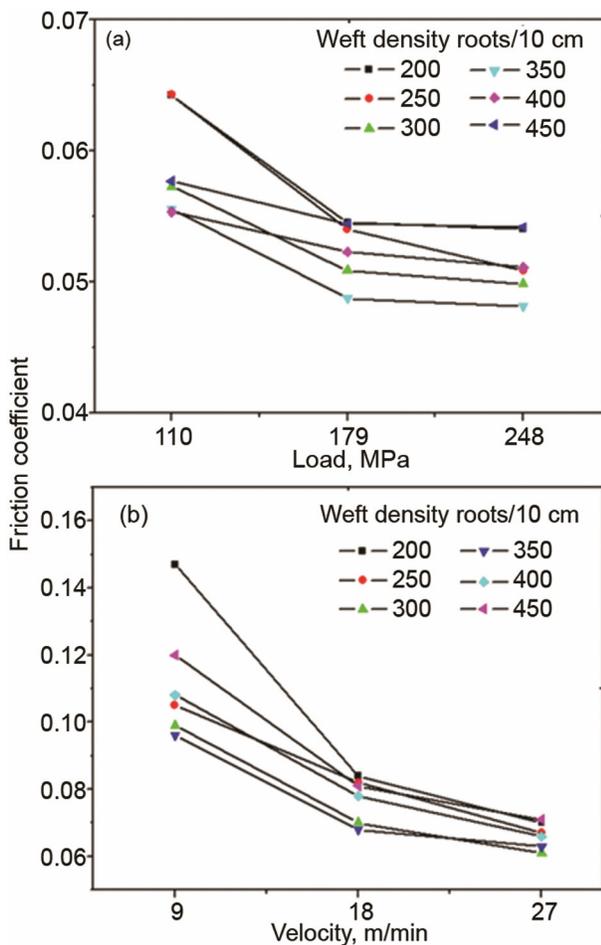


Fig. 3—Friction coefficients under (a) low velocity and heavy load condition, and (b) high velocity and light load condition

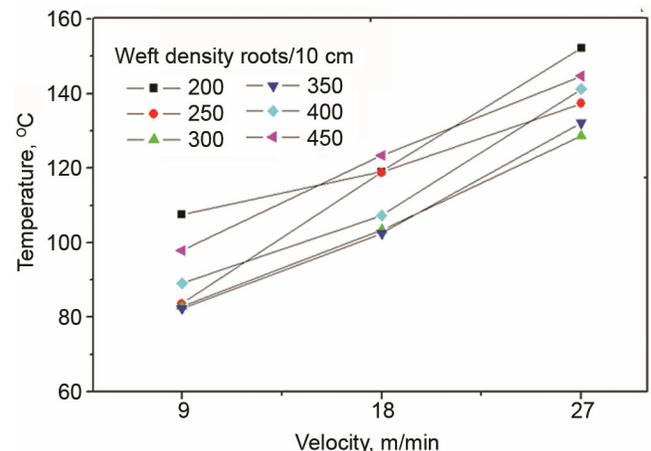


Fig. 4—Liner temperature under high velocity and light load condition

The average values of the liner temperature at each velocity are presented in Fig. 4. Obviously, the temperature rise caused by the velocity increase results in the changes in adhesion resistance and deformation resistance (the two components of friction coefficient), as shown below:

$$f_1 = f_1^0 e^{(\alpha-\gamma)\Delta t} \quad \dots (5)$$

$$f_2 = f_2^0 e^{2\gamma \frac{\alpha \Delta t}{2}} \quad \dots (6)$$

where f_1 is the adhesion friction coefficient; f_2 , the deformation friction coefficient; f_1^0 , the adhesion friction coefficient at initial temperature; f_2^0 , the deformation friction coefficient at initial temperature; α and γ , the temperature coefficients; and Δt , the temperature rise.

It can be seen from Eqs (5) and (6) that the temperature rise affects the liner friction coefficient

exponentially and this is supposed to have greater impact on the friction coefficient than the lubrication film does.

3.2 Wear Rate

The relationships of wear rate, weft density and load/velocity under low/high velocity and heavy/light load conditions are studied and the findings are shown in Fig. 5. Wear rates of liners with different weft densities show almost the same variation in trend as well. Figure 5(a) shows that under low velocity and heavy load condition, the wear rate of the fabric self-lubricating liner decreases with increasing load and this induces the increase in wear loss at the same time. Besides, growth rate of the wear loss is calculated using the following equation:

$$r = \frac{K_2 - K_1}{K_1} \quad \dots (7)$$

where r is the growth rate of wear loss; K_1 , the wear rate of liner under load/speed of 110 MPa/9 m/s; and

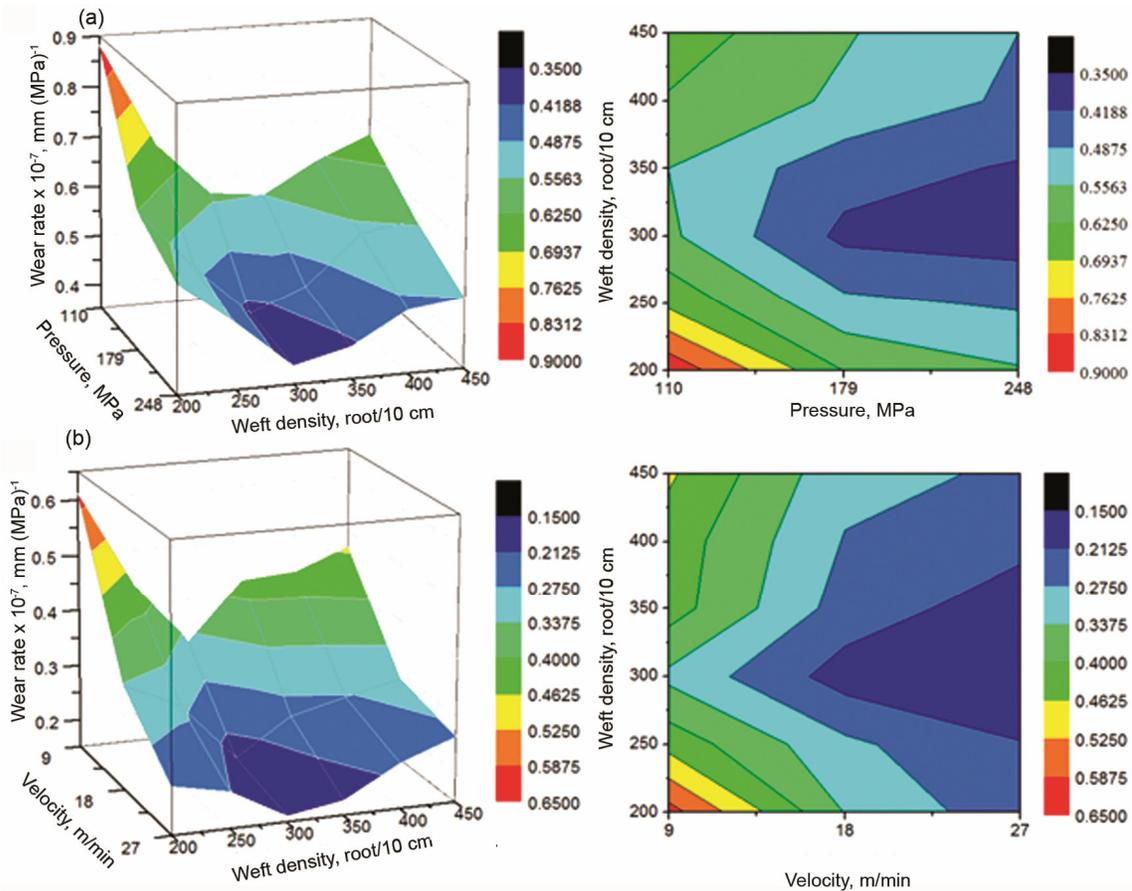


Fig. 5—3D surface graph and wear rate isoline of (a) wear rate, weft density and load under low velocity and heavy load condition, and (b) wear rate, weft density and velocity under high velocity and light load condition

K_2 , the wear rate of liner under load/speed of 248 MPa/27 m/s.

The load is increased by more than 1.25 times when it changes from 110 MPa to 248 MPa. But the growth rates of the wear loss (Table 3) increases by not more than 0.8 times, hence according to Eq. (2) the wear rate reduces. Meanwhile, the weft density affects the wear rate, and the liner with a weft density of 300~350 root/10cm possesses relatively low wear rate. In fact, a larger actual contact area of friction surface induced by load increase ensures that both PTFE and Kevlar fibres are involved in the friction process. Owing to the excellent mechanical properties such as strong tensile strength and shear strength of the Kevlar fibre, the PTFE fibre is protected from being worn off rapidly. In addition, the increasing load and the PTFE and Kevlar fibre debris filled in the valley of the liner decrease the roughness of the liner and more fibres are allowed to participate in friction. In this way, the excellent mechanical properties of Kevlar fibre can help to decrease the wear rate to its highly extent. Figure 5b shows that the variation tendency of wear rates becomes gentler with increasing load. This means that under low velocity and heavy load, the heavier the load, the weaker is the weft tendency to affect the wear rate of self-lubricating liner.

Similarly, there exists almost the same variation tendency of wear rate [Figs 5(a) and (b)]. Table 3 also presents the growth rates of wear depth (h) of self-lubricating liners with different weft densities under high velocity and light load condition, as velocity increases from 9 m/min to 27 m/min. As Eqs (3) and (4) show, in spite of the increase in wear depth (h) with the increasing velocity, the sliding distance triples at the same time. Apparently, the increasing tendency of wear depth (h) is far less than that of the sliding distance (L), which naturally results in the decrease of wear rate K . In addition, on comparing Fig. 5(a) with Fig. 5(b), it is found that the overall level of wear rate of liners with different weft densities under low velocity and heavy load condition is higher than that under high velocity and light load condition and the weft density affects wear rate of the fabric self-lubricating liner.

It is found that the fabric liner with 250-300 root/10cm weft density shows lower growth rate than the other kinds of fabric liner under both working conditions. This property might be induced by the fabric tightness, which is related to weft density of the fabric and the yarn diameter of the fibres. In the present study, the yarn diameters of the PTFE and Kevlar fibres are constant, i.e. 0.1682 mm and 0.1975 mm respectively. Hence, the fabric tightness is dependent on the weft density only. Low weft density of the fabric liner results in low fabric tightness and poor integrity of the weave structure. Under heavy load or high velocity, the weave structure of the fabric liner can hardly maintain integrity and is easily damaged, which causes high wear rate of the fabric liner. The heavier/higher the load/velocity, the more obvious is this phenomenon. Therefore, the growth rate of the wear rate increases. On the other hand, when the weft density is too high, both the fabric planeness and the soaking process during fabrication of the liner are negatively influenced. Normally, too high weft density (fabric tightness) significantly affects the fabric planeness of the woven fabric. Wrinkles emerge on the fabric surface, which decreases the contact area in friction and results in high wear rate. On the other hand, with too high weft density, the resin might fail to be soaked into the gaps between the fibres, which causes poor mechanical properties of the fabric liner. In friction, the fabric liner can be consumed quickly. In a word, too low or high weft density (fabric tightness) induces high growth rate of the wear rate.

3.3 Overall Levels of Friction Coefficient and Wear Rate

On comparing Fig. 4(a) with 4(b) and Fig. 5(a) with 5(b), it is found that liners with different weft densities show higher friction coefficient and lower wear rate under high velocity and light load condition than that obtained under low velocity and heavy load condition. This could be explained by the fact that cold flow (creep) degree of the polymer (PTFE and Kevlar) fibres is higher under low velocity and heavy load condition than that under high velocity and light load condition. Temperature, stress level and time are crucial factors for the creep response of polymeric and

Table 3—Growth rates of wear loss under low/high velocity heavy/light load condition

Weft density, root/10cm	200	250	300	350	400	450
Low velocity heavy load	0.59515	0.43571	0.53333	0.67046	0.72449	0.65714
High velocity light load	0.60417	0.18431	0.13835	0.36211	0.61927	0.42909

polymer composite materials¹⁹. It is well known that PTFE has a second order α -transition at $\sim 130^\circ\text{C}$, but the exact assignment of this transition is still controversial. In any case, this α -relaxation is most likely associated with the motion of large segments in the PTFE amorphous phase²⁰. Occurrence of the cold flow, especially large scale cold flow, could induce the reduction in shear strength even the breakage of the polymer fibre, which is helpful in the deformation of lubricating film but increases the wear rate in the meantime. Under low velocity and heavy load condition, large scale cold flow easily occurred under combine action of extremely heavy load (110~248 MPa) and long experimental time (20 h). On the other hand, cold flow degree dramatically increases when the temperature is at around α -transition temperature. Under high velocity and light load condition, temperature of the liner increases with increasing velocity. When the velocity is reached at 18 and 27 m/min, the temperature arrives at $100\text{--}150^\circ\text{C}$. But the cold flow process is blocked by a short experimental time (2 h), which causes the relatively high friction and low wear rate.

3.4 Wear Morphology

Figure 6 shows the wear morphology of the fabric self-lubricating liner with a weft density of 350 root/10cm under low velocity and heavy load condition and 300 root/10cm under high velocity and light load condition. Compressive deformation of the Kevlar fibres is occurred at a load of 110 MPa and the PTFE fibre is uniformly spread over on the wear surface under the action of shear force. There remains

plenty of debris including PTFE fibre, Kevlar fibre and resin in the dent, as shown in Fig. 6(a), ensures that the liner is in good lubrication state and operation. Figure 6(b) shows that when the load is increased to 179 MPa, the Kevlar fibre along the warp direction is totally subjected to friction with only little debris stored in dent and the lubrication state is getting worse. When the load is 248 MPa, the PTFE lubricating film covering on Kevlar fibre surface is almost completely consumed and severe wear occurs in some area under heavy load [Fig. 6(c)].

At a velocity of 9 m/min [Fig. 6(d)], the resin in the Kevlar and PTFE fibre bulge is worn off and part of the fallen resin is stored in the dent of the liner. The PTFE fibre is worn slightly and the woven structure of the liner remains intact. As the velocity is increased to 18 m/min, obvious plastic deformation in liner tissues appears gradually. The PTFE fibre is spreaded over; the resin layer is peeled off completely and the Kevlar fibre in the warp direction is exposed [Fig. 6(e)]. When the velocity reaches to 27 m/min, a wide range of PTFE fibre is transferred to friction surface and spreaded over uniformly. Meanwhile, the Kevlar fibre is flattened and severe deformation occurs, so that the liner tissues are destroyed and become illegible. It can also be seen that the higher the velocity, the more severe is the wear of PTFE, Kevlar fibre and resin layer. But more uniform PTFE transfer film lowers friction coefficient and protects the fabric from further damage. This could be an evidence to the variations in friction coefficient and wear rate when velocity changes.

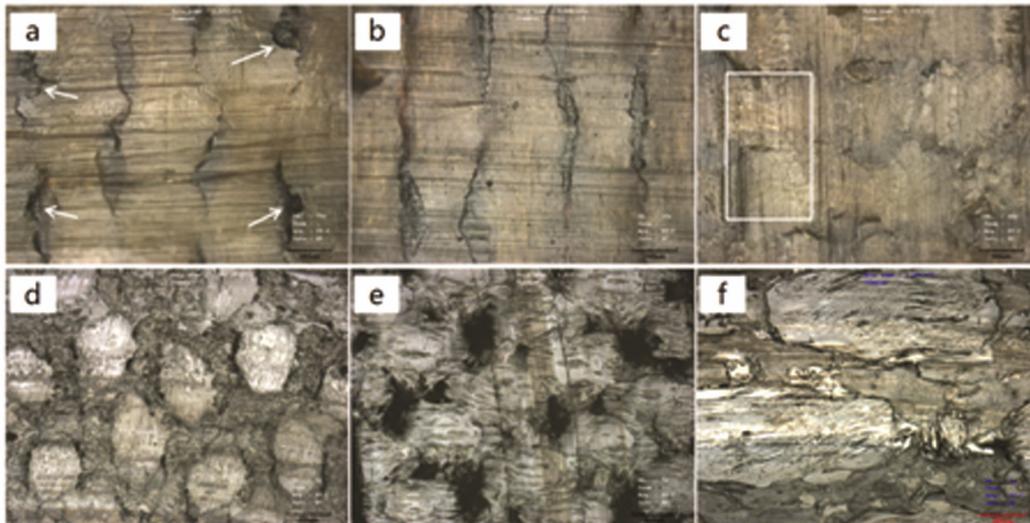


Fig. 6—CLSM wear morphologies of the fabric self-lubricating liner with weft density of 350 root/10cm under heavy load of (a) 110 MPa, (b) 179 MPa, and (c) 248 MPa; and 300 root/10cm under high velocity of (d) 9 m/min, (e) 18 m/min, and (f) 27 m/min

4 Conclusion

The tribological performances of fabric self-lubricating liner with different weft densities under series of severe working conditions have been systematically studied in this paper. The corresponding results are shown as follow:

4.1 Cold flow degree of the polymer (PTFE and Kevlar) influences the overall levels of the friction coefficient and the wear rate of liners with different weft densities under different severe working conditions.

4.2 Weft density affects the tribological property of fabric self-lubricating liner. Proper weft density can improve the tribological properties of the fabric self-lubricating liner. A preferred weft density for the fabric self-lubricating liner under severe working conditions is 300-350 root/10cm. Induced by the fabric tightness, fabric self-lubricating liners with weft density of 250-300 root/10cm show low growth rate of the wear rate and high stability of the wear resistance under severe working conditions.

4.3 Fabric self-lubricating liners with different weft densities share almost the same tribological property variation tendency under severe working conditions, i.e. the variation in tribological properties (friction and wear rate) of the liner has a stable trend of reducing and gradually they are stabilized with increasing load (under low velocity and heavy load condition) or velocity (under high velocity and light load condition).

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