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FRICTION AND ADHESION ENERGY OF POLYMER–POLYMER SLIDING COMBINATIONS

TARCIE I ENERGIA ADHEZJI PODCZAS ŚLIZGANIA W POŁĄCZENIACH POLIMER–POLIMER

Key words:

coefficient of friction, reversible adhesion energy, hardness ratio, polymer––polymer pairs

Słowa kluczowe:

współczynnik tarcia, energia adhezji, wskaźnik twardości, połączenie polimer––polimer

Summary

The friction coefficient, reversible adhesion energy and hardness ratio of polymer-polymer combinations such as PC, PS, PTFE, PA6, LDPE and PP are examined using a pin-on-ring type tribometer. Polycarbonate has been used as a ring material. The applied loads are 10, 20, 30, 40, and 50 N. The coefficient of friction as a function of sliding time, applied load, and hardness ratio has been observed. Additionally, the relationship between the coefficient of friction and reversible adhesion energy calculated from the surface components is

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calculated. The results show that the coefficient of friction is highly dependent on the reversible energy. The coefficient of friction increases as the reversible adhesion energy increases. At a hardness ratio equal to unity, the coefficient of friction exhibits high values. At higher values of the hardness ratio, $H_C/Hp = 2.4$, however, the coefficient of friction possesses low values. In addition, the coefficient of friction is highly dependent on the load applied. It decreases with the increase in the load.

NOMENCLATURE

W_o: The reversible adhesion energy between the two solids S1 (pin) and S2 (ring)
γ_{s1}^{D}:   The dispersive component of the surface free energy of pin material
γ_{s2}^{D}:   The dispersive component of the surface free energy of ring material
γ_{s1}^{P}:   The polar component of the surface free energy of pin material
γ_{s2}^{P}:   The polar component of the surface free energy of ring material
Hc/Hp: Hardness ratio (hardness of the counterface / hardness of the pin)

INTRODUCTION

The applications of polymers in tribological systems as modern technological requirements has increased demands in terms of stability at higher loads, temperature, and better lubrication and wear properties. In many instances, the use of polymers represents a good tool to improve the tribological properties of mechanical components sliding over each other. However, frictional self-excited vibration in the polymer on the polymer sliding pairs has not received much attention. Jia et al [L. 1] studied the friction and wear properties of some polymeric materials. They showed that the friction and anti-wear properties could be greatly improved by oil lubrication (PTEE & PPS), while in the case of PA6, those properties (wear and friction) were compromised by oil lubrication. Also, the frictional heat, which would alter the physical state of polymer sliding surfaces, had a significant effect on the in tribological behaviour of the polymer on the polymer sliding combinations under dry sliding conditions. Maede el al [L. 2] studied the adhesion and friction mechanisms of polymer on polymer surfaces. They stated that polymer-polymer adhesion hysteresis and friction depend on the dynamic rearrangement of the outer most polymer segments at shearing interfaces. Pan et al [L. 3] found that an optimal solid lubricant film was obtained at graphite content of 50 %, which led to the lowest friction coefficient and wear rate due to a possible dynamic equilibrium between the transfer and spalling of debris. Eiss et al [L. 4] have studied the effect of surface roughness, normal load, sliding velocity, and silicon oil content of acrylonitrile-butadiene-styrene polymer on the friction

coefficient in the case of dry sliding. They have found that stick-slip occurs on the smooth surface at high loads for materials which possess a negatively sloped friction–velocity curve at lower velocities and a positive slope at higher velocities. The friction of polymer depends to a large extent upon interfacial adhesion **[L. 5]** for modified polyeythylenes. Momozono et al **[L. 6]** showed that the results of the adhesion and friction experiments are compared with those of a simplified formula based on power law or logarithmic approximations of a previous adhesive friction model. They pointed out that, the results provide additional evidence supporting the assumptions in their earlier frictional model. Yamada **[L.7]** pointed out that the specific wear rate of a given polymer in a polymer on polymer sliding combination depends on the mated polymeric material and that a high wear rate is observed in sliding against a polymer counterface with the cohesive energy density higher than that of the slider.

The aim of this work is to study the friction of PC, PS, PTFE, PA6, PP and LDPE for dry sliding on PC surface. The coefficient of friction as a function of sliding time, applied load, hardness ratio and reversible adhesion energy is obtained. The reversible adhesion energy is calculated from the surface energy components.

EXPERIMENTAL DETAILS

Six types of polymers (PC, PS, PTFE, PA6, PP and LDPE) are used as square pins (8mm x 8mm) with PC rings (50mm diameter and 10 mm thickness) as a pin-on-ring tribometer. The applied loads are 10, 20, 30, 40 and 50N, and the coefficient friction is recorded as a function of time. Experiments are performed at ambient temperature and 40% relative humidity. The sliding speed is 0.5 m/s and the surface roughness of ring surface is set as (Ra = = 0.15 µm). In order to ensure that the pin and ring are coplanar, the pins are initially rubbed against an abrasive paper of grit 800. The tensile strength (σu), ultimate elongation (ε_u), tensile modulus of elasticity (E), and hardness (HRC) of the tested materials are given in **Table 1**, and the polar component γ_s as components of the surface free energy **[L. 8]** are shows in **Table 2**. If only physical dispersive and non-dispersive van der Waals forces are responsible for the interfacial adhesion, the reversible adhesion energy (W_O) for the different couples can be calculated from their respective surface energy components. According to Lavielle **[L. 5],** the reversible adhesion energy between two solids S_1 and S_2 can be written as follows:

Reversible Adhesion Energy

The values of the dispersive component γ_s^D

$$W_o = 2(\gamma_{s1}^D \ \gamma_{s2}^D)^{1/2} + 2(\gamma_{s1}^P \ \gamma_{s2}^P)^{1/2} \tag{1}$$

Table 1. Mechanical and physical properties of used polymers
Tabela 1. Własności mechaniczne i fizyczne wykorzystanych polimerów

PS	PTFE	LDPE	PP	PA	PC	
48	17	14	34	81	62	σu (MPa)
15	200	150	75	60	110	εu(%)
3000	410	158	1400	2800	2400	E
65	50	45	110	118	120	HRC

Table 2. Surface energy components and reversible adhesion energy
Tabela 2. Składowe energii powierzchniowej i odwracalnej energii adhezji

W_o(mJ.m^{-2})	γ_s(mJ.m^{-2})	γ_s (mJ.m^{-2})	
84.00	0.8	41.2	PC
86.45	6.2	40.8	PA6
69.40	1.7	27.3	PP
73.74	0.0	33.0	LDPE
56.62	0.5	18.6	PTFE
83.95	0.6	41.4	PC

RESULTS AND DISCUSSIONS

Figure 1 shows frictional behaviours obtained in a polymer on polymer interaction for the investigated polymer at v = 0.5m/s, Ra = 0.15 µm and P = 20N. It could be seen that, in the case of PC/PP and PC/PA6 (**Fig. 1a** and **1b**), the coefficient of friction is almost constant, steady-state case, and it has a low value, µ= 0.084-0.094. On the other hand, in the case of PC/PS and PC/PC (**Fig. 1c** and **1d**), the coefficient of friction in the initial sliding stage are about 0.17 and stick slip oscillation is observed and the coefficient of friction reached to 0.166 after sliding time of 1800 sec.

Due to the good sliding properties of polyethylene and polytetrafl..roethylene, **Fig. 1e** and **1f**, the coefficient of friction has low value, µ = 0.13, and it decreases or is still constant with sliding time due to the transfer film of polyethylene to the ring surface. But this film becomes thicker after 500 sec of sliding time and the friction process changes to the friction between LDPE or PTFE pin and itself, a process that results with a slight increase in the friction coefficient. **Figure 2** shows the coefficient of friction versus sliding time of polymer–polymer pairs at different loads. It has been observed that, in most polymer–polymer sliding combinations, the coefficient of friction is relatively high at start-up sliding stage, and it decreases to a lower level as the sliding time increased. In the case of PC slid against PP, **Fig. 2a,** generally, the coefficient of friction in the start-up stage range from 0.10-0.015.
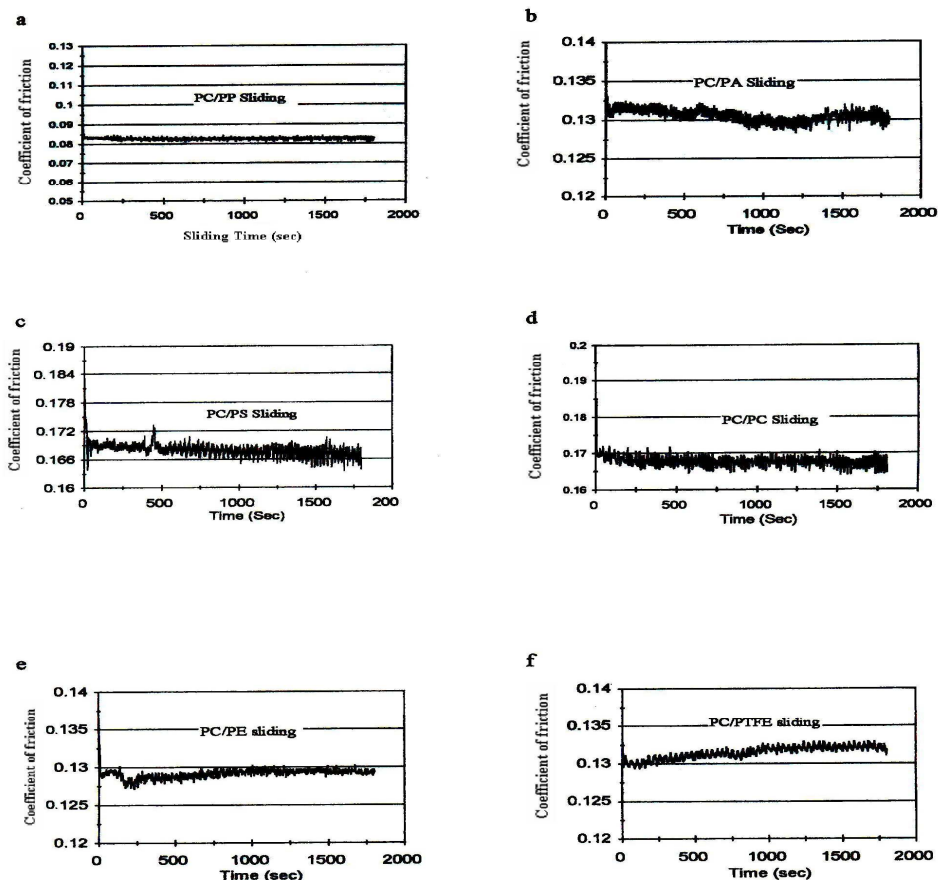
Fig. 1. Friction coefficient versus sliding time at V = 0.5 m/s and P = 20 N
Rys. 1. Współczynnik tarcia w funkcji czasu ślizgania przy prędkości V = 0,5 m/s i obciążeniu
P = 20 N

But after a sliding time of 30 min, the coefficient of friction shows lower values, 0.06-0.12 under all the applied loads. This may be due to the formation of the transfer film that may be effective in reducing friction. In the case of PC/ PA, **Fig. 2b**, the coefficient of friction of the start-up stage ranges from 0.16-0.20 and decreases gradually with sliding time, up to 20 min, then remains constant. In the case of PC/ PTFE, **Fig. 2f,** the coefficient of friction decreases in the start-up stage of friction, up to 10 min sliding time, then increases with time (up to 20 min.) and stabilises at a given level. This may be referred to the formation of a thin film that is transferred to the PC ring surface resulting in a reduction in the friction. After a certain time, the transfer film will be thicker
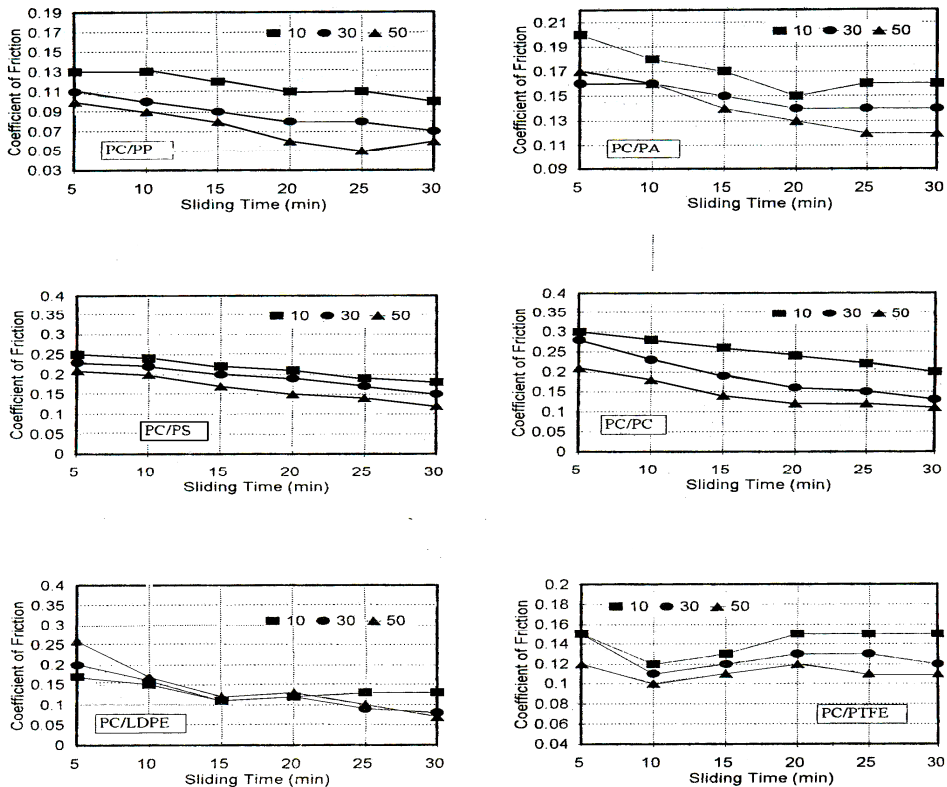
Fig. 2. Relationships between friction coefficient and sliding time at V= 0.5 m/s, Ra = 0.15
Rys. 2. Zależność pomiędzy współczynnikiem tarcia i czasem ślizgania przy V= 0,5 m/s, Ra = 0,15

and tends to change the friction state to adhesive friction. In adhesion studies, it is well known that the adhesion of a polymer surface rubbing against another polymer is strong, which results in an increase in the friction force. In case the of PC/ PC, **Fig. 2d**, the friction coefficient in the start-up sliding stage is relatively high, 02-0.3, and decreases gradually with sliding time. But in the case of PC/ PS, **Fig. 2c**, the friction coefficient is relatively high and almost independent of both sliding time and applied load. This may be attributed to the absence of a transfer film of PS to the ring surface. From **Fig. 2e,** PC/ PTFE, it can be seen that the coefficient of friction decreases rapidly from 0.25 at the start-up sliding stage to about 0.07 after a sliding time of 30 min at p = 50N. This may be referred to the effective transfer film of PTFE to the PC surface that results in reducing the friction coefficient. Generally, in all case studies, the friction coefficient exhibits lower values at higher values of the load applied.

    Figure 3 shows the coefficient of friction as a function of the applied load for the investigated polymer combinations. It can be seen that the friction

coefficient of polymer-polymer sliding pairs is highly dependent on applied load for a smooth surface (Ra = 0.15 µm). It possesses, however, lower values at high loads. Also, from **Fig. 3**, the friction coefficient of the brittle pairs PC/ PA6 and PC/ PC indicates higher values, while for brittle/ductile pairs (PC/ PTFE and PC/ PP), the friction coefficient has lower values. This may be referred to the relatively high glass transition temperature of the brittle polymer (Tg = 100 and 150 $^{\circ}$C for PS and PC, respectively) and semi-ductile polymer (Tg = 65 $^{\circ}$C for PA). The rise of friction in this case could be attributed to the real area of contact in such a manner that the friction force increases with load.
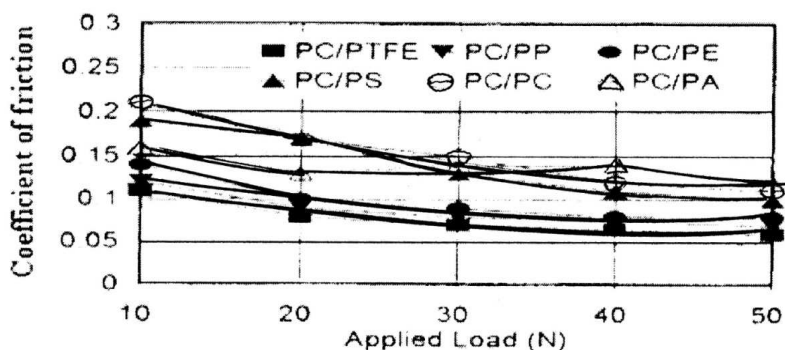

Fig. 3. Dependence of coefficient of friction on applied load for polymer-polymer combinations
Rys. 3. Zależność współczynnika tarcia od obciążenia dla badanych połączeń polimer-polimer

Figure 4 shows the coefficient of friction as a function of the calculated reversible adhesion energy W_o for polymer–polymer sliding at different loads. As shown in **Figure 4**, the increase of the reversible adhesion energy tends to raise the friction coefficient. This may be referred to the increase in the adhesion force at the interface **[L. 1].** Also, it can be seen that the reversible adhesion energy for ductile polymers (PTFE, PP and LDPE) is smaller than for semi-ductile (brittle) polymers, such as PS, PC and PA6.

Figure 5 shows the influence of the hardness ratio (H_C/Hp) on the friction coefficient at V = 0.5 m/s and at different loads. It can be noticed that, at H_C/Hp = 1.0, the coefficient of friction indicates high values, while at high values of the hardness ratio, H_C/Hp = 2.4, the friction coefficient exhibits low values. It can be stated that interfacial properties and bulk mechanical properties have an influence on this adhesion. If the interfacial adhesion is high (H_C/Hp = 1.0), the bulk mechanical properties often play a greater role on increase the friction coefficient than the other case (H_C/Hp = 2.4). For this reason, when a polycarbonate rubs against itself, H_C/Hp = 1.0, the coefficient of friction is

high. This behaviour is due to the high interfacial adhesion that results in no transfer film between the two rubbing surfaces (severe friction process). At high values of the hardness ratio, $H_C/Hp = 2.4$, the counterface is a brittle polymer (PC) and the pin is a ductile one (PTFE), the adhesion energy is low. This may be responsible for the transfer a thin film of PTFE to the counterface, which moderates the friction process.
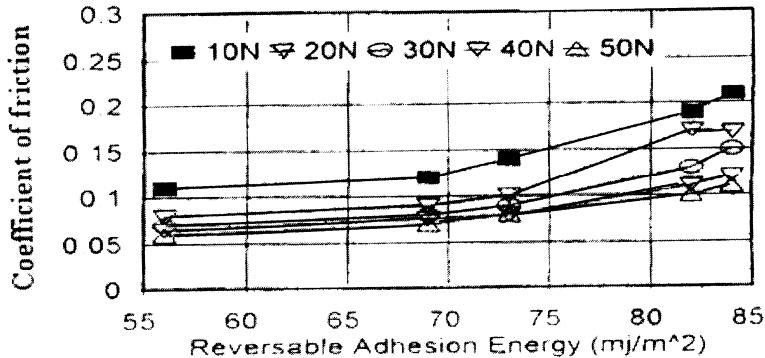

Fig. 4. Coefficient of friction versus reversible adhesion energy
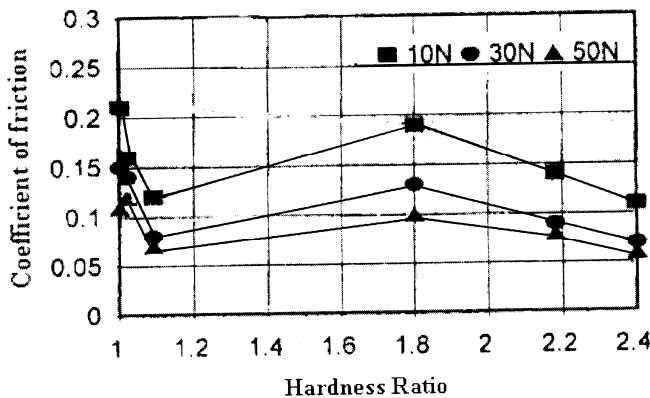Rys. 4. Zależność współczynnika tarcia od odwracalnej energii adhezji

Fig. 5. Dependence of coefficient of friction on hardness ratio for polymer–polymer combinations
Rys. 5. Zależność współczynnika tarcia od wskaźnika twardości

CONCLUSIONS

From the above results of polymer-polymer sliding pairs, the following conclusions can be drawn:
1. The coefficient of friction increases slightly with increasing the reversible adhesion energy up to 70 mJ/m^2 after which it highly increases. For the

ductile polymer (PTFE, PP and LDPE) the reversible adhesion energy is less than that for the brittle polymers such as PS, PC and PA6.

2. At a hardness ratio equal to unity, the friction coefficient exhibits higher values than those in the case of a hardness ratio, $H_C/H_P = 2.4$.

3. The coefficient of friction is highly dependent on the load applied and is inversely proportional to the load applied.

4. When a polycarbonate rubs against itself, PC/PC, the coefficient of friction is relatively high due to the high energy of adhesion.

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Streszczenie

W pracy przedstawiono wyniki badań współczynnika tarcia, odwracalnej energii adhezji i stosunku twardości połączeń polimer-polimer, takich jak PC, PS, PTFE, PA6, LDPE i PP, które określano przy użyciu testera typu trzpień–pierścień. Na materiał pierścienia wykorzystano poliwęglan. Zastosowano obciążenia 10, 20, 30, 40 i 50N. Obserwowano zmianę współczynnika tarcia w funkcji czasu ślizgania, przyłożonego obciążenia i wskaźnika twardości. Ponadto obliczano zależność pomiędzy współczynnikiem tarcia i odwracalną energią adhezji. Wyniki pokazują, że współczynnik tarcia jest bardzo zależny od energii adhezji. Współczynnik tarcia

wzrasta wraz ze wzrostem energii adhezji. Przy jednakowej twardości materiałów współczynnik tarcia przyjmuje wysokie wartości. Przy wyższych wartościach wskaźnika twardości, $H_C/Hp = 2.4$, współczynnik tarcia ma małą wartość. Dodatkowo, współczynnik tarcia bardzo zależy od przyłożonego obciążenia – jego wartość maleje wraz ze wzrostem obciążenia.