

Characteristics and mechanism of abrasive wear for thermoplastic polymers

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Abstract: Abrasive wear characteristics of polyethylene, polystyrene, polymethylmethacrylate, nylon 1010 and polyvinyl chloride were investigated. The volume relative wear resistance coefficients of these thermoplastic polymers are 18%-35% (hardened and low temperature tempered steel 45 was used as a comparing material), and have a linear correlation with square roots of their cohesive energy densities. The coefficients of linear correlation is 0.949. Wear morphologies were observed by scanning electron microscope (SEM). Main wear mechanism of the thermoplastic polymers includes brittle breaking for the hard and brittle polymers & plowing and fatiguing for the soft and tough ones.

Key words: polymer; abrasive wear; wear mechanism; cohesive energy

Polymer materials have many good performances, such as low density, high specific strength, high electro-insulating property and good corrosion resistance. Up till now, they have partially replaced some metal materials and inorganic materials as components of sliding friction pairs. Some of them have become essential materials in the some fields of industry and science technology [1]. There have been many investigations [2-7] mainly focused on the friction-wear performance of sliding friction of polymers, but the great majority of polymers have a poor abrasive wear resistance, their abrasive wear mechanism needs to investigate further. In this paper, abrasive wear characteristics and mechanism of polyethylene, polystyrene, polymethylmethacrylate, nylon1010, and polyvinyl chloride were investigated.

1 Experimental

Polyethylene (PE), polystyrene (PS), polymethylmethacrylate (PMMA), polyvinyl chloride (PVC), and nylon1010 (PA1010) were used in experiment, hardened and low-temperature tempered steel 45 as a comparing materials. The size of specimen is 60 mm × 35 mm × 6 mm. The friction-wear testing machine is turntable wear machine JMM made in China, its schematic sketch is shown in **figure 1**. Three polymer specimens and one comparing material specimen were fixed on clamping apparatus at the same time. Every specimen was in wear position in turn, in which wear distance was 803.4 m each time. Specimen in wear position did not move, turntable turned in 49 r/min

and brought abrasive materials to move. This resulted in a relative movement between specimen and abrasive materials in the speed of 123.6 m/min. Abrasive materials consisted of 450-900 μm quartz sands of 92.8 %, alta-mud of 3.4%, and water of 3.8 % (mass fraction). Total wear distance of each specimen was 16068 m, the buried depth of specimen was 40 mm, the angle between the normal of wear surface and the line from wear surface to circle center was 35° ± 10'.

Wear resistance was represented in volume relative wear resistance coefficient (ε_{vi}).

$$\varepsilon_{vi} = V_c / V_i \times 100\% \quad (1)$$

where V_c and V_i are volume wear loss of comparative specimen and volume wear loss of tested polymer specimen, respectively. The average value of 9 specimens' ε_{vi} was taken as the wear resistance of each material and was shown in $\bar{\varepsilon}_v$.

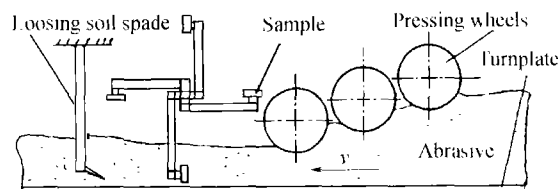


Figure 1 Schematic drawing of wear test equipment.

2 Results and discussion

The volume relative wear resistance coefficient of PE, PS, PMMA, PVC, and PA1010 are listed in **table 1**. $\bar{\varepsilon}_v$ and the square root of cohesive energy ($\sqrt{E_c}$)

have a good linear correlation with linear correlation coefficient 0.949, the linear correlation equation is obtained as follows:

$$\overline{\varepsilon}_v = -14.38 + 2.07 \sqrt{E_c} \quad (2)$$

However, linear correlation coefficients of $\overline{\varepsilon}_v$ to impact toughness, hardness, and tensile strength are 0.213, 0.402, and 0.745, respectively, *i.e.*, they are much smaller than 0.949.

Table 1 Wear resistance and other relative properties of polymers

Polymer	Cohesive energy / (J·cm ⁻³)	Hardness (HRM)	Tensile strength / MPa	Impact toughness / (kJ·m ⁻²)	$\overline{\varepsilon}_v$ / %
PE	249	45	29.5	10.0	18
PS	303	75	49.0	1.7	21
PMMA	346	90	66.3	2.0	22
PVC	369	60	53.9	3.2	29
PA1010	587	85	73.5	5.0	35

Note: The properties, except wear resistance, are quoted from references [8-10].

Because of PMMA with amorphous structure, PVC with some extent crystallinity, and PA1010 with some hydrogen bonds, the equation (1) obtained from them can be used to estimate wear resistance of other thermoplastic polymers.

Cohesive energy is an energy for overcoming intermolecular force. The formation of abrasive dust needs to overcome the intermolecular force between it and substrate, wear resistance increases with the increase of cohesive energy of materials. Side groups like acylamino existing in main chains of molecules, which can increase cohesive energy, can make polymers have the better wear resistance. But if side groups are too large, they will lower the molecule packing density and crystallinity, and decrease cohesive energy and wear resistance. PA1010 not only has hydrogen bonds, whose bond energy is higher than that of Van der Waale bond, but also has some extent crystal. So it has better wear resistance. Other polymers in this study with the amorphous structure or lower crystallinity have worse wear resistance.

E. Rbinowicz [11,12] suggested that when wear dusts come off from substrate, the elastic energy stored in it must equal or exceed the adhesion energy binding it on its substrate. For a hemispherical wear dust, the elastic energy stored in it is given by equation (3):

$$E_v = \frac{1}{2}(\sigma_r^2 / E)(\pi d^3 / 12) \quad (3)$$

where E_v is the elastic energy stored in a wear dust, σ_r is the residual stress in the wear dust, E is Young modulus and d is the diameter of hemispheric wear dust. The adhesion energy is given by equation (4):

$$E_s = W_{ab}\pi d^2/4 \quad (4)$$

where E_s is the adhesion energy, W_{ab} is the adhesion work. When E_v is equal to or the larger than E_s , the loose wear dust forms. From above analysis, it can be

concluded that the larger the adhesion energy E_s is, the better the wear resistance of materials is.

Ashok K. Vijh [13] reported that the abrasive wear resistance of metals and inorganic non-metals is determined by the cohesion (*i.e.*, the bonding strength) of these materials. The bonding strength can be calculated by following equation:

$$B(M-M) = 2\Delta H_s/N_C \quad (5)$$

where $B(M-M)$ is the bonding strength, ΔH_s is the heat change of sublimation of metals and N_C is bulk coordination number. Therefore, the larger the bonding strength is, the better the wear resistance. This study shows that above rules are fit for thermoplastic polymers.

The results shown in table 1 have a good agreement with the conclusions in references [11-13] and shows that the hardness, strength and impact toughness of thermoplastic polymers obviously influence the wear mechanism. The morphologies of worn surfaces of polymer samples are shown in **figure 2**.

From figure 2, it can be found that there are deep furrows in the worn surface of PE, and plastic deformation ribbons exist at two sides of furrows. For PS, many cracks parallel to the moving direction of abrasive particles formed in the ridgy plastic deformation ribbons. Furrows with smooth surface exist in worn surfaces of PMMA samples and the plastic deformation at the two sides of furrows is non-evident. The crack and broken zone form in worn surfaces along the moving direction of abrasive particles. In worn surfaces of PVC samples, shallow furrows and plastic deformation ribbons form along the moving direction of abrasive particles. The crack vertical to moving direction of abrasive particles form in the plastic deformation ribbons. It is similar to that of PS, but wave deformation and tongue plastic deformation form in the plastic deformation ribbons and cracks are induced

at the root of tongues. For PA1010, there are only slight furrows and plastic deformation in the worn surface.

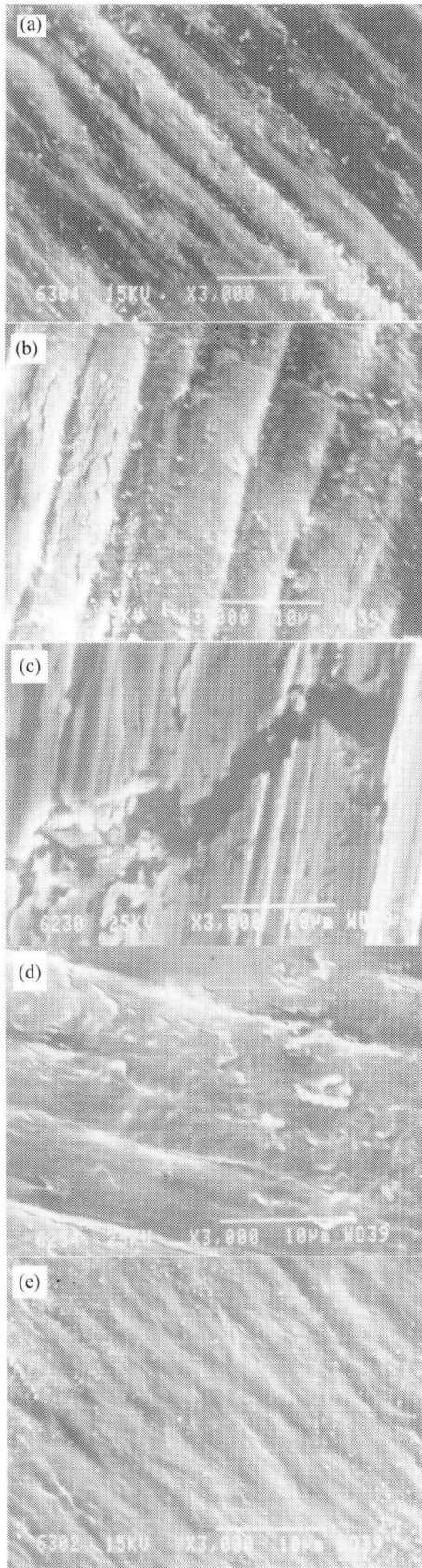


Figure 2 Wear morphologies of polymers, (a) PE; (b) PS; (c) PMMA; (d) PVC; and (e) PA1010.

From worn surface morphologies of samples, it can

be found that abrasive wear of thermoplastic polymers can be classified into two parts qualitatively, and described as follows:

$$W = k_1/H + k_2/G \quad (6)$$

where W is wear loss, H and G are hardness and fracture toughness respectively, k_1 represents wear coefficient from ploughing and plastic deformation and k_2 represents wear coefficient from brittle break. *i.e.*, in the equation (6), the first item k_1/H represents the wear loss from ploughing and plastic deformation, and the second item k_2/G represents the wear loss from brittle break. Therefore the prevailing wear mechanism depends on properties of thermoplastic polymers. The changes of wear mechanism with the changes of k_1 and k_2 are shown in figure 3. It shows that when both k_1 and k_2 are 0, abrasive particles can only make the wear surface of samples deform (shown in figure 2(a)). When k_2 is 0 and k_1 is not 0, ploughing and deformation take place in the wear surface (shown in figure 2(b)). When k_1 is 0 and k_2 is not 0, brittle break form in the wear surface (shown in figure 2(c)). When both k_1 and k_2 are not 0, there are not only ploughing and deformation, but also brittle break in the wear surface of specimen (shown in figure 2(d)).

PE has a lower hardness. When the abrasive particle with some energy slides along the surface of samples, its edges and corners will cut into the surface of samples by the action of normal force, and plough the surface of samples to form furrows with plastic deformation by the action of tangential force. This wear process may be completed by one-time action of one abrasive particle, but in general cases, by many-time actions of many abrasive particles. Based on above analysis, ploughing is the prevailing wear mechanism of PE.

The hardness and strength of PS are much higher than that of PE, so the surface of PS sample is ploughed a little by abrasive particles, but appears to be obvious plastic deformation at two sides of furrows as shown in figure 4 (a). In this case, generally, one time action of one abrasive particle can not result in the wear, but repeated actions of many abrasive particles can result in the formation of cracks due to the fatigue deformation of ridgy plastic deformation ribbons. The propagation and intersection of cracks lead to the formation of wear dusts, as shown in figure 4(b). Therefore the wear loss of PS can be explained by fatigue deformation.

PMMA also has the higher hardness and strength, abrasive particles can only slightly plough the wear surface of PMMA and make it deform little as shown

in figure 3(c). Brittle break dominates the wear behavior. The movement of abrasive particles can produce heavy local stress in the surface of samples. In the front of abrasive particles press stress forms, and behind abrasive particles tensile stress forms. Because PMMA is very brittle, lateral cracks vertical to mov-

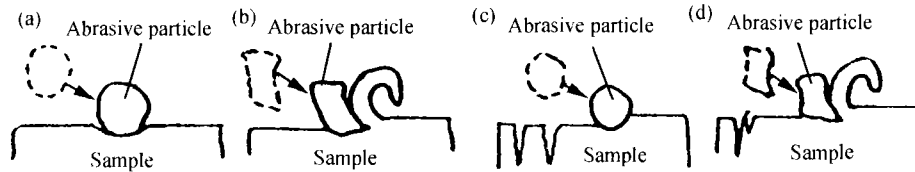


Figure 3 Schematic drawing of changes for wear mechanism; (a) elastic deformation ($k_1 = 0, k_2 = 0$); (b) plowing and deformation ($k_1 \neq 0, k_2 = 0$), (c) breaking ($k_1 = 0, k_2 \neq 0$), (d) ploughing, deformation and breaking ($k_1 \neq 0, k_2 \neq 0$).

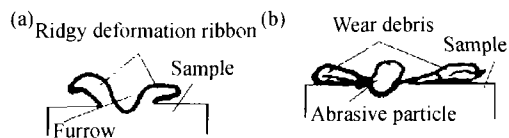


Figure 4 Schematic drawing for formation of ridgy deformation ribbons (a) and formation of wear debris (b).

PVC has the lower hardness, higher tensile strength and impact toughness. Abrasive particles can plough its wear surface a little, its brittleness is not enough to make it form lateral cracks. Wear grooves and plastic deformation ribbons along longitudinal cracks form in the worn surface like the case of PS. Because PVC also has a good toughness, the formation of wear dusts by fatigue break of plastic deformation ribbons will take longer time. Micro-zone deformations form in the deformation ribbons, which appear to be wave shape at starting time, soon afterwards, they change into tongue shape, then cracks form at the root of tongues, tongues break at their roots and form wear dusts.

Because PA1010 has not only higher hardness but also good strength and toughness, abrasive particles can only produce slight ploughing and plastic deformation on its wear surface, and it is difficult to form brittle break. Comparing with PE, PS, PMMA, and PVC, PA1010 has better wear resistance.

3 Conclusions

For thermoplastic polymers, volume relative resistance coefficient of abrasive wear is positive rate to the square root of their cohesive energy.

The hardness, strength and toughness of thermoplastic polymers control wear mechanism. If they are not only hard but also brittle, prevailing wear mechanism of thermoplastic polymers is brittle break, but if they have a good toughness, prevailing wear mechanism is fatigue deformation.

The volume relative wear resistance coefficient of thermoplastic polymers is 18%-35% comparing with

ing direction of abrasive particles are produced by the action of tensile stress and normal force. The repeated action of many abrasive particles induces cracks to extend and intersect, in the end, form wear dusts. Obviously, the dominant wear mechanism of PMMA is brittle break.

that of hardened steel 45.

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