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Abrasive Wear Mechanisms of Sand Particles Intruding into ATM Roller-scraper Tribosystem

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Abstract: The roller-scraper tribosystem of automatic teller machine (ATM) plays an important role in reliable cash requests. However, the abrasive wear of the polymer tribosystem becomes a prominent problem when operating in sandy environment. The wear behavior of the tribosystem in a simulated sandy environment has been experimentally studied previously. However the abrasive wear mechanism of roller-scraper tribosystems is still unknown to new design. The wear rates of polymer rollers were examined comprehensively and several jumping variations were found in the full data extent. Three wear stages were classified by the magnitude of wear rates, and different dominant wear mechanisms corresponding with different particle diameter were found by examining the worn surfaces. Accordingly a presumption was proposed that wear mechanisms in different stages were correlated with sand particles of different diameter. In a verification experiment, three typical wear mechanisms including cutting, ploughing, and wedging were found corresponding with different wear stages by scanning electron microscope(SEM) examination. A theoretical analysis was carried out with a simplified sphere particle intrusion model and the transfer conditions for different wear mechanisms were studied referring to the slip-field theory. As a main result, three typical wear models versus friction coefficient of particle/roller, and particle radius were mapped with variant hardness of the polymer roller and ratio of contact shear stress to bulk shear stress. The result illuminated the abrasive wear mechanism during particle intrusion. Particularly，the critical transition conditions gave the basis for improving the wear performance of roller-scraper tribosystems in a sandy environment.

Key words: tribosystem, abrasive wear, mechanism

1 Introduction

Roller-scraper tribosystems in automatic teller machine (ATM) play an important role in processing cash requests accurately and reliably. However, the earlier failure of polymer roller due to the abrasive wear by sand dust particles is becoming a big problem for ATMs when servicing in a contaminated air environment with high sand dust content. The tribological performance of polymer roller in a contaminated environment was found, in previous studies[1–3], highly determined by the intrusion of sand particles into roller-scraper tribosystems. Therefore, the abrasive wear mechanism of polymer roller during particle intrusion need to be investigated furthermore for improving the wear performance of ATMs.

Abrasive wear mechanisms of polymers are very complex with its elastic-plastic nature[4]. A detailed category of polymer deformation during abrasion has been reported[5–6]. Ploughing, cutting, and wedging mechanisms happened in polyresin were mapped with the conditions of normal loads and indenter angles. Similar results in metals were reported by HOKKIRIGAWA, et al [7]. Three abrasive wear mechanisms were clearly observed in metal substrates under different penetration degrees. So it is reasonable to accept that the category of abrasive wear mechanisms is suitable both for polymers and metals. Furthermore, the models of ploughing, cutting, and wedging were theoretically analyzed by CHALLEN, et al[8] using slip-line field theory. The result explained successfully the abrasive wear in an ideal pyramid scratching test. Also, the effects of abrasive particle diameter on wear rate were investigated with diverse conclusions[9–10]. However, the abrasive wear behaviors of polymer by sand dust particle have scarcely been investigated, which is important with polymers becoming popular in industrial applications.

The critical condition for sand particle intruding into a roller-scraper tribosystems was studied [11]. To get further understand, in this research, a comprehensive analysis of the abrasive wear mechanisms in particle intruding is carried out incorporating with the previous experimental results. In section 2, the experiment is described and primary data was reviewed. In section 3, a theoretical analysis is presented. Consequently, the determinant factors on abrasive wear mechanisms are investigated in section 4,

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followed by discussions and conclusions.

2 Experiment

2.1 Experiment description

The sketch of a roller-scraper tribosystems derived from ATMS was discussed elsewhere[1]. The physical model of a spherical particle intruding into roller-scraper tribosystems is given in Fig. 1. A particle is pressed against roller surface under the pressure of a scraper by means of spring. The particle can move on the roller surface when intruding. The scraper rotates around the central point O''. Polymer to polymer tribopair is specified for this experiment.

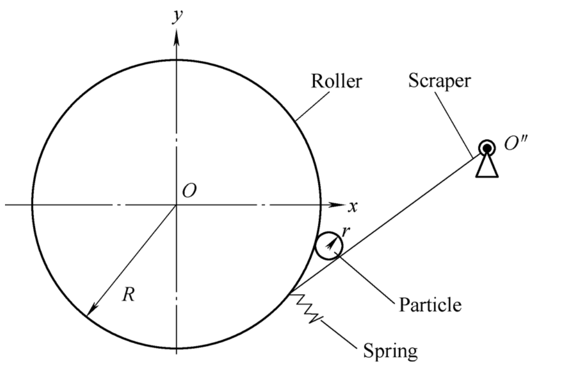


Fig. 1. Simplified model of spherical particle intruding into roller-scraper tribosystem

The experiment was carried out in a simulated sand dust environment[11]. The sand particles deposited onto the surfaces of the roller, and intruded into the tribopairs by friction effect. The friction coefficient and the worn cross -section profile of the polymer roller were measured consistently. The wear mechanism of the polymer roller was investigated by the in-situ observation with optical microscope and by finial examination with scanning electron microscope (SEM).

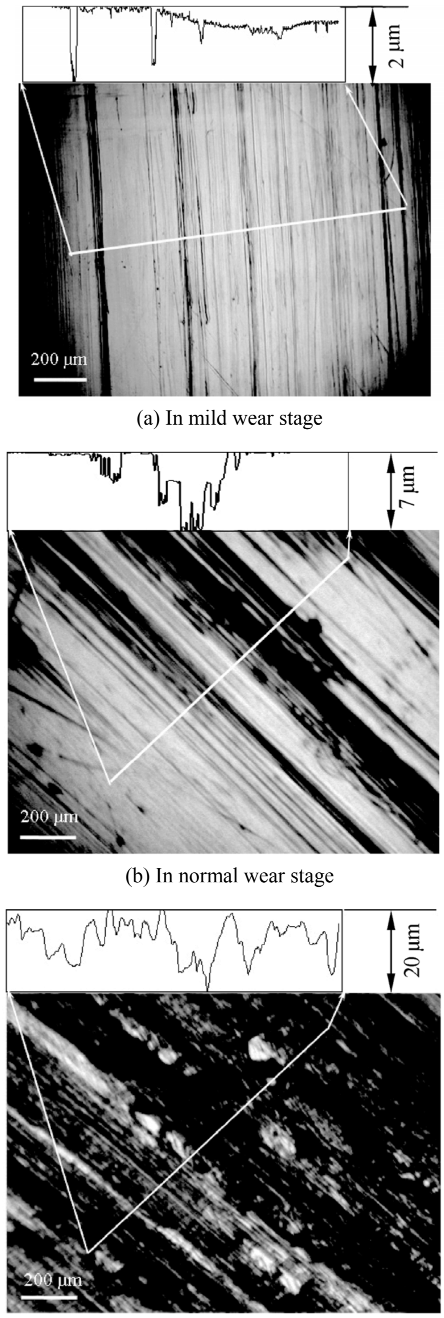
2.2 Experimental result analysis

Generally, wear rates variation could be induced by wear mechanism change. Different wear rates were found in the roller wear process[11], which indicated the variation of wear mechanisms. According to the range of wear rate magnitude, the wear process was classified into three wear stages as given in Table.

Table. Wear stage category

Wear stage	Range of wear rate magnitude
Mild wear	Below 10^{-5}
Normal wear	10^{-5}–10^{-4}
Severe wear	Over 10^{-3}

The corresponding optical photos of the worn surfaces are given in Fig. 2. The comparison shows that different damages happened in different wear stages. And the depth and width of scratching grooves increases corresponding with different wear stages, which is produced by intruding particles in different diameters. In details, Fig. 2(a) shows many micro-cutting grooves by tiny particles, and the deepest groove is about 2 μm. Fig. 2(b) shows deeper and wider grooves produced by some small particles, and the deepest groove is about 7 μm. Fig. 2(c) shows a fully damaged surfaces produced by large particles, and the deepest groove is about 20 μm.



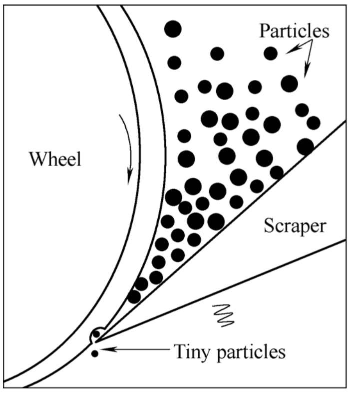
(a) In mild wear stage

(b) In normal wear stage

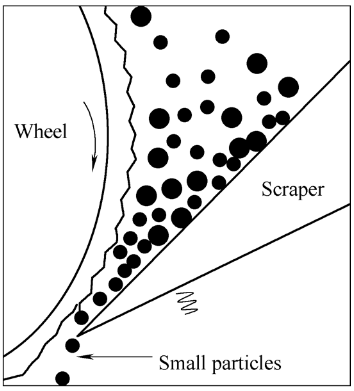
(c) In severe wear stage

Fig. 2. Corresponding optical photos and typical cross section profile of the worn surfaces with different wear stages

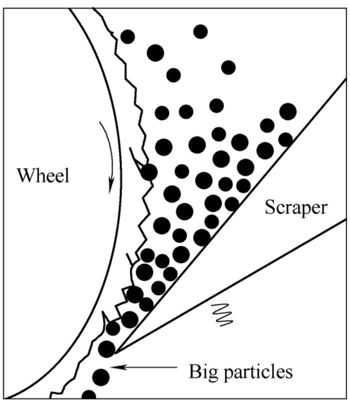
According to the experimental results, a presumption is proposed as shown in Fig. 3. Roller surface is smooth at the initial stage as shown in Fig. 3(a) and only little tiny particles can be dragged by electrostatic and friction force into tribopairs. Tiny particles, as sharp abrasive by itself, are prone to produce micro-cutting on soft roller surface as shown in Fig. 3(b). As wear proceeding, roller surface is getting rougher and some small abrasive particles participated in the abrasion. Deformation due to indentation of small particles increase, and cutting is getting difficult. Some ploughing grooves are produced. In the severe wear stage, as shown in Fig. 3(c), most large particles intrude into the tribopair and aggravate the worn surface, which are prone to produced wedging and blocking than ploughing or cutting in soft material. In a word, particles in different diameters produce different wear mechanism.



(a) Mild wear



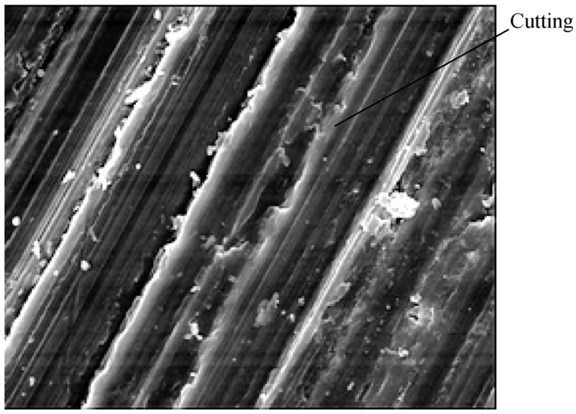
(b) Normal wear



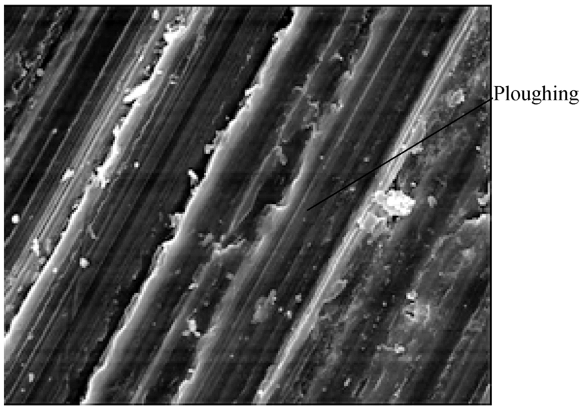
(c) Severe wear

Fig. 3. Assumption model for different wear stages

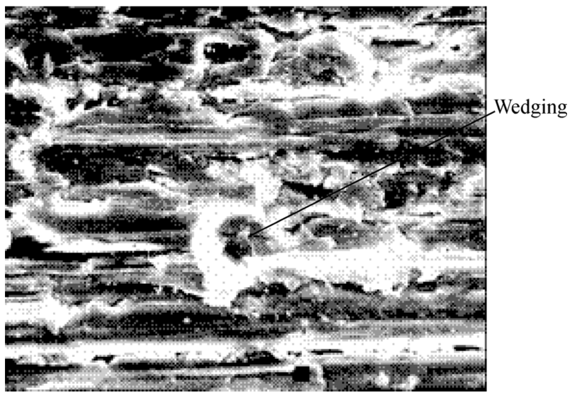
To verifying the presumption, more detailed experiments were designed to examine the wear mechanisms in different wear stages. Figs. 4(a)–4(c) shows the typical SEM examination results. Three dominant abrasive wear mechanisms including cutting, ploughing, and wedging were found on the worn surfaces corresponding with different wear stages. For comparison, a similar result was given in Fig. 4(d)–4(f) [6].



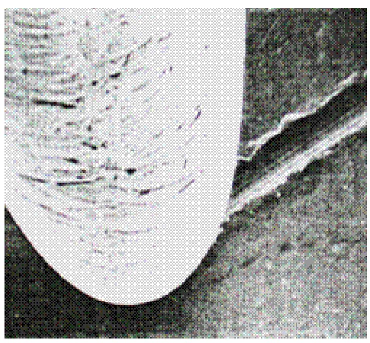
(a) Cutting in the roller ×500



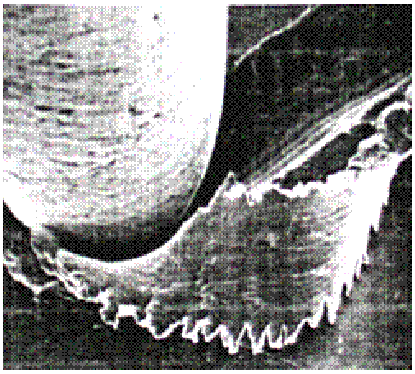
(b) Ploughing in the roller ×500



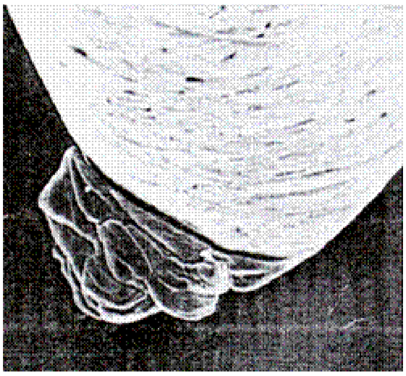
(c) Wedging in the roller ×500



(d) Cutting in the metal



(e) Ploughing in the metal



(f) Wedging in the metal

Fig. 4. Typical wear mechanisms in the roller comparing with that in Ref. [7]

Different abrasive wear mechanisms were exactly realized by using diamond indenter with various radiuses. In this study, particles in different diameters are similar to diamond indenters with different radius. However, the dimension of grooves in polymer is not as uniform as that in metal because of particles in various dimensions in abrasive.

3 Theoretical Analysis

Particle intruding is a complex process including many different mechanisms corresponding with different intruding particles simultaneously. However, the quantitative description of particle intruding is necessary for improving tribological performance. The principle of particle intruding has been analyzed in previous, and a theoretical analysis was made in this work with the slip-line field model.

Some hypothesis was used in the following analysis: (1) The particle is a hard sphere. (2) The particle rolling is not considered and only one dimension motion is considered. (3) The deformation of the scraper fluid is neglected. (4) Only one particle intruding is occurred.

According to the model of HOKKIRIGAWA, et al[7], the critical condition and the friction coefficient for each model were determined by the attacking angle θ of the hard asperity and a non-dimensional parameter f (the ratio of contact shear stress to bulk shear stress). Attacking angle is a geometric parameter, and therefore needs to be investigated in a new model. The penetration of a sphere particle into a flat roller surface is illustrated in Fig. 5.

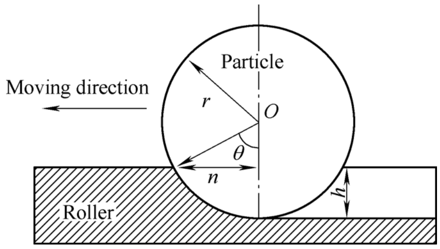


Fig. 5. Penetration of a sphere particle into a roller surface

The penetration degree is denoted by the attacking angle θ as

$$D_{\mathrm{p}} = \frac{h}{n} = \frac{r}{n} - \left(\frac{r^2}{n^2} - 1\right)^{\frac{1}{2}} = \tan\frac{\theta}{2}, \quad (1)$$

where D_{p}—Penetration degree,
h—Penetration depth,
n—Radius of contact hemicycle,
r —Particle radius,
θ —Attacking angle.

In plastic contact, the contact pressure can be treated as the hardness of the softer roller H:

$$\frac{w}{H} = \frac{\pi n^2}{2}, \quad (2)$$

where w—Applied load on single particle,
n—Radius of contact hemicycle,
H—Hardness of polymer roller.

With Eqs. (1) and (2), D_{p} can be rewritten as

$$D_{\mathrm{p}} = r\left(\frac{\pi H}{2w}\right)^{\frac{1}{2}} - \left(\frac{\pi H}{2w} r^2 - 1\right)^{\frac{1}{2}}. \quad (3)$$

Therefore, the attacking angle θ can be calculated with the parameters in this case. And then the wear mechanisms of particle intruding were analyzed with the reference model[7–8].

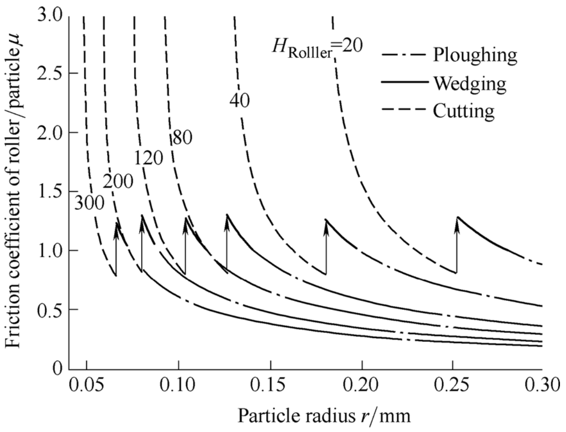
4 Result and Discussion

Four variables are included in the wear model. To facilitate the analysis, some parameters were fixed. The critical conditions for three wear models were calculated and the corresponding friction coefficients of roller/particle, μ, in different wear models were calculated.

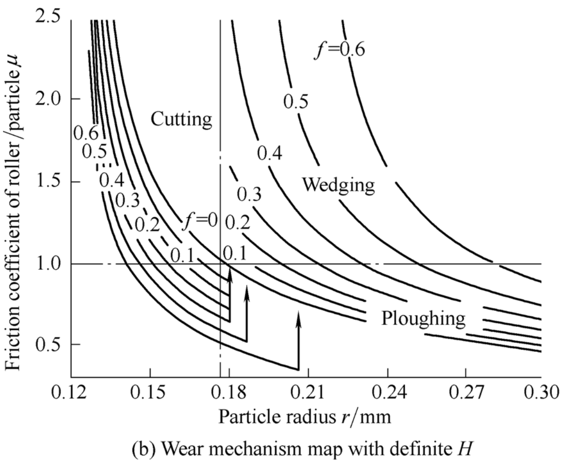
The calculating conditions were particle radius ranging from 0.01 mm to 0.3 mm, H ranging from 20 MPa to 300 MPa, f ranging from 0.1 to 0.6, and applied load 1 N.

Fig. 6(a) shows the variations of μ with particle radius with fixed f. With definite H, abrasive wear models are transferred from cutting to wedge forming and to ploughing with increase of particle radius. With H increases, critical particle radius for wear models decreases. That means cutting is easier to be produced by smaller particles and wedge forming; and ploughing is easier to be produced by larger particles. Harder roller is prone to be damaged by abrasive wear. That means that the abrasive wear models in intrusion can be selected by changing the roller hardness in design. In addition, cutting shows generally higher friction coefficient than other two mechanisms even though produce light wear by small particles.

Fig. 6(b) shows the variation effects of f on the wear models with fixed H. Three wear models were mapped by two perpendicular dot lines as shown in Fig. 6(b). With f increases, the critical particle radius for cutting model decreases, and that for ploughing model increases. That means the material easy to be sheared is prone to be cut other than wedged or ploughed.



(a) Wear mechanism map with definite f



(b) Wear mechanism map with definite H

Fig. 6. Wear mode maps of sphere particle intruding into roller-scraper tribosystem

The wear model maps generally give the rational relationship between particle diameters and wear models. However, there are still big diverges of the quantitative correspondence between the models with the experimental results, e.g., the critical particle radius and the friction coefficient. Reasonable explanations can be made as follows. Some idealizations were used, e.g., sphere particle other than irregular one was considered in this model, and some wear mechanisms besides abrasive wear, e.g. fatigue and spalling, were omitted.

Accordingly, some useful means were drawn for improving the wear performance of polymer roller when operating in a dust environment. Intruding particles and the wear models can be selected by designing material parameter H and interface parameter f, and μ, which gives a new way to improve the wear performance of ATMs in contaminated environment.

5 Conclusions

(1) Three wear stages were categorized according to the magnitude of wear rates and the corresponding wear mechanisms were analyzed by examined the worn surfaces.

(2) A presumed wear model including three wear stages was put forward considering particle diameters. Three abrasive wear mechanisms including cutting, wedging, and ploughing were experimentally found in different wear stages.

(3) With slip-line theory, three abrasive wear mechanisms were mapped with variable parameters H, f, μ, and r. The critical conditions for transition of different abrasive wear mechanisms were clarified, which gave the basis of improving wear performance in the material design of roller-scraper tribosystems.

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