Tribology Online
Japanese Society of Tribologists

Tribology Online, 3, 7 (2008) 370-375.
ISSN 1881-2198
DOI 10.2474/trol.3.370

Tribology in Natural Sand Dust Environment

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(Manuscript received 2 September 2008; accepted 2 December 2008; published 31 December 2008)
(Presented at the International Session, JAST Tribology Conference Nagoya, September 2008)

The tribological problem in natural sand dust environment was proposed and an equipment for simulating the natural sand dust environment based on Multi-Venturi structure was introduced for studying the tribological problem. The wear performance of polymer tapes in sand dust environment was evaluated by using a roller-scraper tribosystem. Three typical wear models including cutting, wedge forming and ploughing during the intrusion of sand particle into the contact interface of polymer materials were found. The abrasive wear mechanisms were discussed with particle intrusion mechanism.

Keywords: tribology, natural sand dust environment, abrasive wear, particle, intrusion

1. Introduction

The natural sand dust environment due to the sand storm has attracted worldwide concern in these years. Taklamakan desert has been clarified as the main source of Asia sand storm. Large amount of sand dust including multi-scale particles has been transported from the Taklamakan desert in Northwest China to Korea and Japan by the sand storm. The dust environment with high falling dust deposition flux caused by the sand storm has been found as a big tribo-harm to various machines.

Tendency of high precise and reliability of mechanical products requires more adaptability to their service environments in the design criterion. The air quality of the service environment has an effect on the lifetime of mechanical products, and the dust content of the air is a sensitive factor. Generally dust particles carried by air flow can intrude into machine system and destruct their stability by various means, for example, aggravating the wear between tribo-pairs as abrasive particles, or degrading the ability of heat elimination by depositing on the device surface, or decaying the optical and electric signal and so on.

In this paper, firstly the equipment for simulating natural sand dust environment is submitted. Secondly, we study the wear properties of polymer types in the natural sand dust environment using the roller-scraper tribosystem. Finally, in order to get better understanding of the tribological problem in nature sand dust environment, we make the analysis on the critical condition for the intrusion of a spherical particle into a contact interface and the condition for the transition of abrasive wear models with the particle intrusion is also discussed.

2. Equipment for simulating sand dust environment

Venturi structure was considered for simulating a uniform sand dust deposition field. The structure of single-Venturi is shown in Fig. 1. The air flow velocity field and sand particle track field were analyzed with FLUENT software. The velocity of 20 m/s was used as the inlet condition, and the atmosphere pressure was the outlet condition. The simulation principle is as follows: at first the air flow velocity field is calculated with Navier-Stokes equation, and then the particle tracks are computed by using the Rosin-Rammler particle distribution model. The uniformity of sand dust particle disposition was evaluated by an index of quality distribution uniformity as follows:

$$s = \sqrt{\frac{1}{n-1}\sum_{j=1}^{n}(x_j - \bar{x})^2} \quad (1)$$

where s is the index of quality distribution evenness degree, x is particle quality, n is the particle number passing though a plane in working chamber.

To make comparison, the distribution of particle trace depicted by particle residence time (s) in single, two and three-Venturi structure was calculated respectively. The simulation results of sand particle track field are shown in Fig. 2. The properties of natural sand dust particles are shown in Table 1. It can be seen from these figures that the three-Venturi structure improved particle distribution uniformity than others. Also, the index of quality distribution uniformity of particle tracks for the three structures was calculated to be 0.25, 0.11 and 0.05 for single, two and three-Venturi structure, respectively. From these data, we understand that the three-Venturi structure has better uniformity than others.

Accordingly, the equipment with nine-Venturi structure was designed for simulating sand dust environment, which is shown in Fig. 3. Its working mechanism is as follows, (1) putting sand dust particles into the sand supply device; (2) setting an air flow power by the controller (3) blowing the particles to the simulator through three-Venturi diffuser with a flux. In order to simulate a natural environment, the humidity and temperature were also controlled.

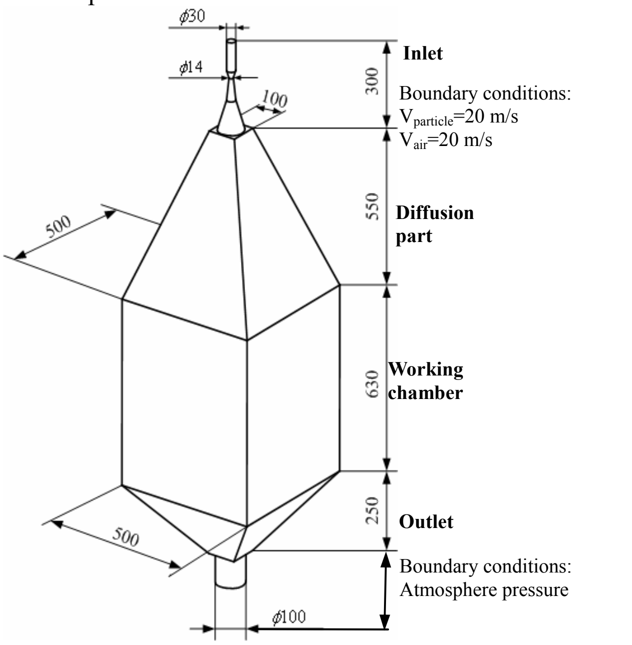


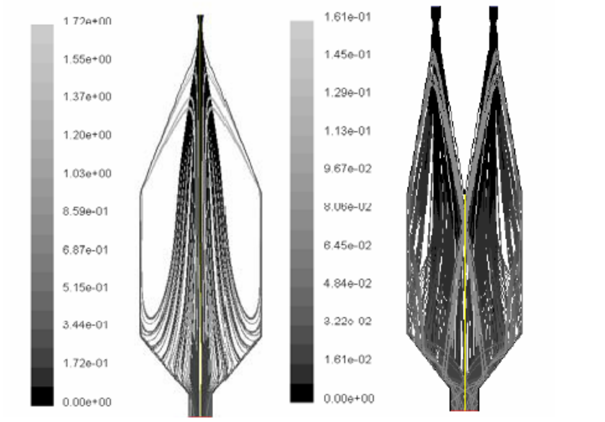
Fig.1 Simulation model with single Venturi structure

Table 1 Properties of the natural sand particle

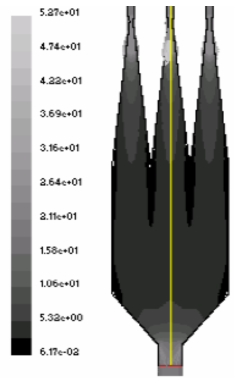
Main oxide	SiO_2	Al_2O_3	CaO	Tfe_2O_3	MgO
Composition (%)	65.32	9.6	8.75	3.05	1.93
Average density(kg/m^3): 2.4×10^3					
Particle size range: 0.69-300 μm					

3. Experimental results

Two polymer tapes for ATM (Auto Teller Machine) were tested in the sand dust environment with the roller-scraper tribosystem as shown in Fig. 4[1]. The polymer tape was winded around the wheel. The bill was used as the substrates under the tape to obtain a close simulation of the real working condition. The



(a) Single Venturi structure (b) Two-Venturi structure



(c) Three-Venturi structure

Fig.2 Simulation results of particle tracks in three Venturi structure

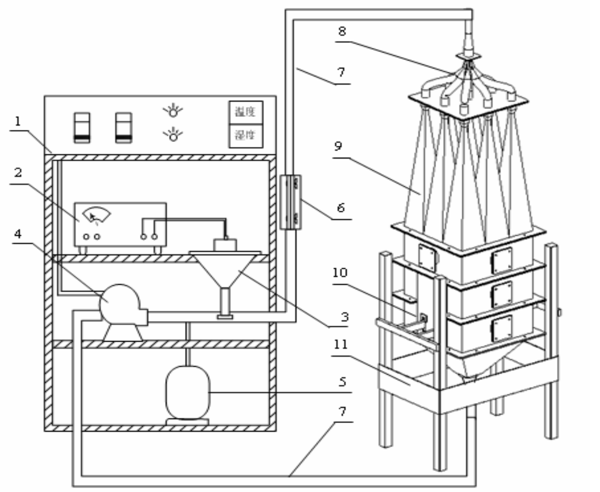


Fig.3 Schematic diagram of the sand dust environment simulator(1-control casing; 2-direct current source; 3- sand supply device; 4-air blower; 5-humidity chamber; 6-secondary filter; 7-blast tube; 8-sand distributor; 9-multi-Venturi diffuser; 10-environment simulator; 11-support frame)

polymer scraper was dragged to contact with the tape surface at a specified force by means of spring. The rotation of the wheel is such that its contact face moves in the direction against sand flow invasion. Two kinds of the sand dust environment were simulated in this experiment, the sand storm environment with the SDF (Sand Deposition Flux) of about 50 kg/m^2·day, and the severe sand storm environment with the SDF of about 960 kg/m^2·day. As a comparison, the experimental results in the clean air environment were given. The test conditions were as follows: load was 0.6,1.0,1.5 N, sliding speed was 1.6 m/s and natural sand particle was in the range of 0.69-300 μm.

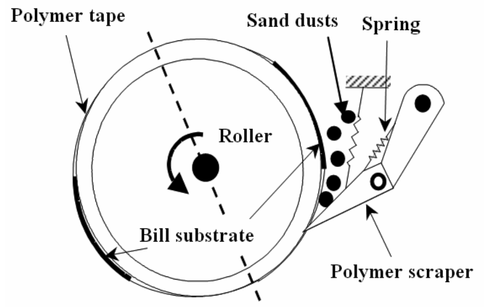
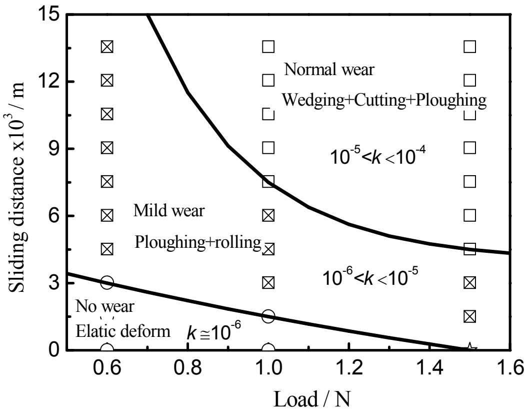
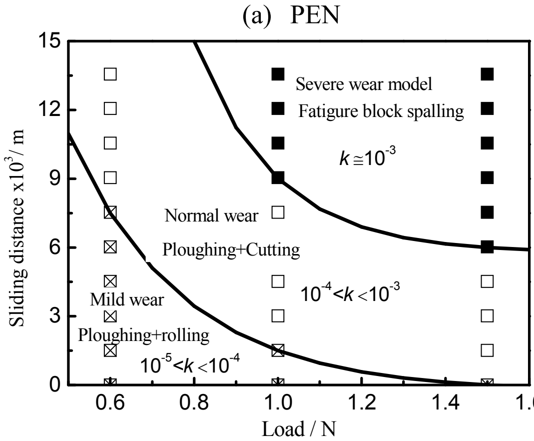


Fig.4 Schematic diagram of ATM roller-scraper tribosystem[1)]



(a) PEN



(b) PI

Fig.5 Wear map of polymers in sand dust environment
k - wear rate, mm^3/N.m

Figure 5 shows the experimental results. The wear models of no wear, mild wear, normal wear and severe wear were found from the wear experiments with different wear rates. The corresponding abrasive wear mechanism for the each wear model is given by Fig. 6. The typical scanning electron micrographs of the worn PI tape surface in different wear stages are shown corresponding with typical photos by Hokkirgawa and Kato[3)]. In cutting model, no chip was found, but the cutting grooves without ridges gave the evidence of cutting behavior. In wedge forming model, the build-up phenomenon indicated wedge formation. In ploughing model, the ridges over the two sides of grooves were main character of ploughing. Because of the size of sand dust particles were in wide range, it is reasonable to believe that the particles in different sizes intruded into the tribopairs during the wear experiment, and caused different wear degrees. Therefore, the relation between intrusion particle and wear mechanism needs to be discussed furthermore.

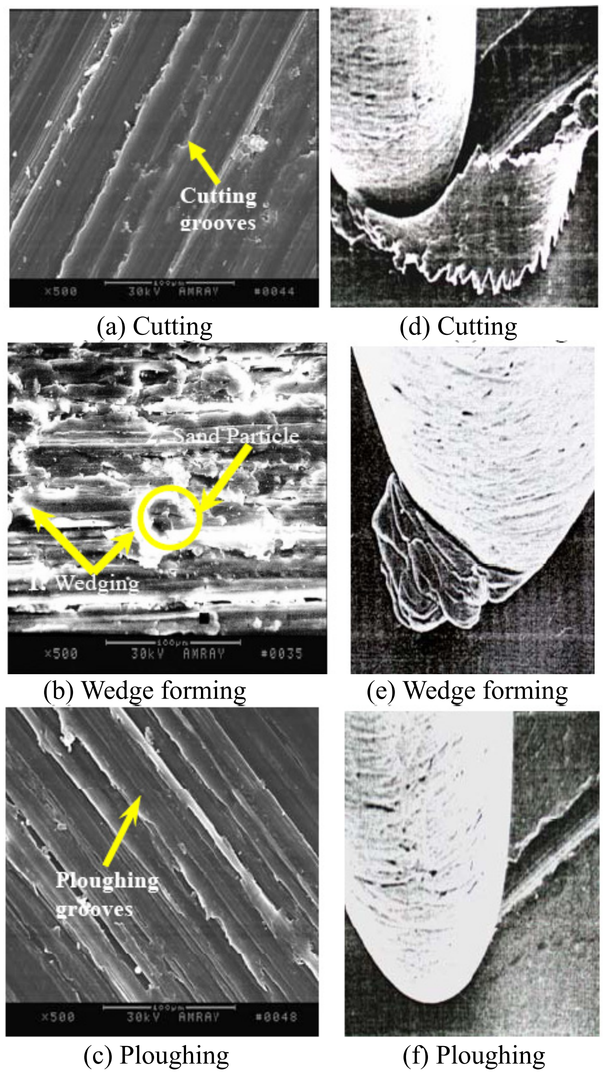


Fig.6 Typical abrasive wear mechanisms of: (a)-(c) polyimide tape; (d)-(f) metal[2)]

Figure 7 shows a comparison of the mean wear rate of two polymer tapes in natural sand dust environment. It is clarified that there are great differences between the wear rate of polymer tape in the clean air environment and in the two sand dust environments. For PEN (polyethylene) tape, the mean wear rate in the sand storm environment is about 500 times of that in the clean air environment. For PI (polyimide) tape, the mean wear rate in the sand storm environment is about 1700 times of that in the clean air environment. The PEN tape exhibits higher mean wear rate than the PI tape in same condition.

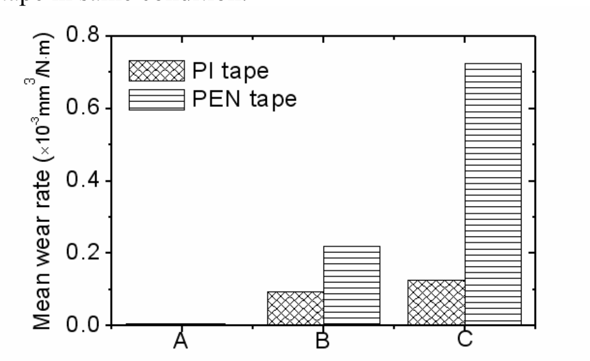


Fig.7 Mean wear rates of PEN and PI tape in clean air environment and in sand storm environments. A-Clean air environment, B-Sand storm environment, C-Severe sand storm environment[1)]

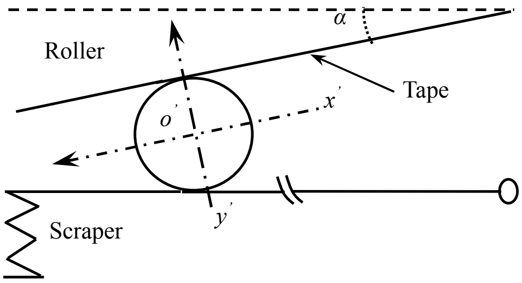
4. Analysis and discussions

4.1. Intrusion conditions

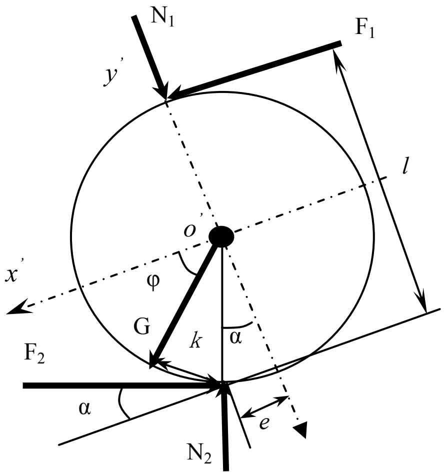
Three typical wear models including cutting, wedge forming and ploughing during the intrusion of sand particle into the contact interface of polymer materials were found in above section. The following, we discuss the abrasive wear mechanisms from the particle intrusion mechanism.

The intrusion model of a spherical particle into the roller-scraper tribosystem was investigated at first. For this purpose, a simplified invasion model and corresponding force diagram of particle is shown in Fig. 8. Considering the force acting on the particle, the particle contacts the tape within a small area, on which act normal force and frictional force. It is convenient that the normal and frictional forces are treated as a normal force N_1 and a frictional force F_1 respectively at contact point. In the same way, the particle contacts with the scraper, where, N_2 and F_2 act.

A coordinate system of $x'o'y'$ is used in Fig.8 (a) to facilitate the intrusion analysis in considering of the invasion direction. So the motion of particle in $o'y'$ direction equal to zero and the resultant force is also equal to zero. The motion in x' direction leads to the invasion and the resultant force in $o'x'$ direction is the invasion force. Now, we have equations under the assumption that the weight of the abrasive itself was neglected.



(a) Simplified invasion model of particle into roller-scraper tribosystem



(b) Force diagram of particle in intrusion

Fig.8 The simplified invasion model of particle into the interface of tape and scraper

In $o'y'$ direction:

$$N_1 + G\sin\varphi - N_2\cos(\alpha) + F_2\sin(\alpha) = 0 \quad (1)$$

In $o'x'$ direction:

$$F = F_1 + G\cos\varphi - N_2\sin(\alpha) - F_2\cos(\alpha) \quad (2)$$

where, G is the gravity of particle, F is invasion force, α is intrusion angle, N_1, N_2, F_1, and F_2 are applied forces respectively. Considering the definition of the friction coefficient ($\mu = F/N$), and substituting N_1 from equation (1) into equation (2), then invasion force equation is as follows:

$$F = \mu_1(-G\sin\varphi + N_2\cos\alpha - \mu_2 N_2\sin\alpha) + G\cos\varphi - N_2\sin\alpha - \mu_2 N_2\cos\alpha \quad (3)$$

Here, μ_1 and μ_2 are friction coefficients of particles against the tape and the scraper separately.

And if taking the contact point of particle with tape as torque centre of the forces, the torque expression is as follows:

$$\tau = F_1 l + Gk - N_1 e \quad (4)$$

Here, τ is resultant torque; l and e are the arms of F_1 and N_1 respectively. The arm of force, l and e, can be denoted by the radius, r, and the angle, α, as $l=r(1+\cos\alpha)$, $e=r\sin\alpha$, and $k=r\sin\varphi$, then the equation (4) can be written into:

$$\tau = N_1\mu_1(r + r\cos\alpha) - N_1 r\sin\alpha + Gr\sin\varphi \quad (5)$$

With equations (3)-(5), the intrusion conditions and the moving patterns of the particle were discussed as follows.

Case 1: $F > 0$

The particle can invade into the interface anyway. And the invasion condition can be introduced from equation (3) as the following;

$$\mu_1 > \frac{G\cos\varphi - N_2\sin\alpha - \mu_2 N_2\cos\alpha}{G\sin\varphi - N_2\cos\alpha + \mu_2 N_2\sin\alpha)} \quad (6)$$

Concerning the moving pattern (rolling or sliding) of the particle in the invasion process, it can be determined by using torque equation (5), i.e., when $\tau > 0$, the particle is rolling; when $\tau = 0$, the particle is sliding. With the equation (5), the condition for moving pattern can be given as following:

$$\mu_1 > \frac{\sin\alpha(N_2\cos\alpha - \mu_2 N_2\sin\alpha - G\sin\varphi) - G\sin\varphi}{(N_2\cos\alpha - \mu_2 N_2\sin\alpha - G\sin\varphi)(1+\cos\alpha)} \quad (7)$$

(for rolling)

$$\mu_1 = \frac{\sin\alpha(N_2\cos\alpha - \mu_2 N_2\sin\alpha - G\sin\varphi) - G\sin\varphi}{(N_2\cos\alpha - \mu_2 N_2\sin\alpha - G\sin\varphi)(1+\cos\alpha)} \quad (8)$$

(for sliding)

Case 2: $F = 0$

The particle can intrude into tribopairs only in the case of $\tau > 0$. And only pure rolling happens in this case.

Case 3: $F < 0$

No intrusion happens anyway. All the results of particle intrusion are summarized in Fig. 9 as the function of friction coefficients. It is clear that the critical condition for particle intrusion does not depend on the particle size strongly. It can be understood from the force diagram that the surface force is not considered here.

4.2. Intrusion mechanisms

The intrusion by sand particles is a complex process including many different wear mechanisms for different particles simultaneously. The abrasive wear map of polyresin developed by Briscoe[3)] with single abrasive cone has given the similar mechanisms with that found by Hokkirgawa and Kato[2)] in metals.

The abrasive wear mechanisms of ploughing, cutting and wedge formation of both the metal and the polymer are highly decided by the attack angle or penetration depth of the hard asperity or cone in contact. The penetration of a sphere particle into a flat roller surface was described in Fig. 10 and the penetration degree was denoted by the attacking angle as follows:

$$D_p = \frac{h}{n} = \tan\frac{\theta}{2} \quad (9)$$

where D_p is penetration degree, h is penetration depth, n is the radius of contact zone, θ is attack angle.

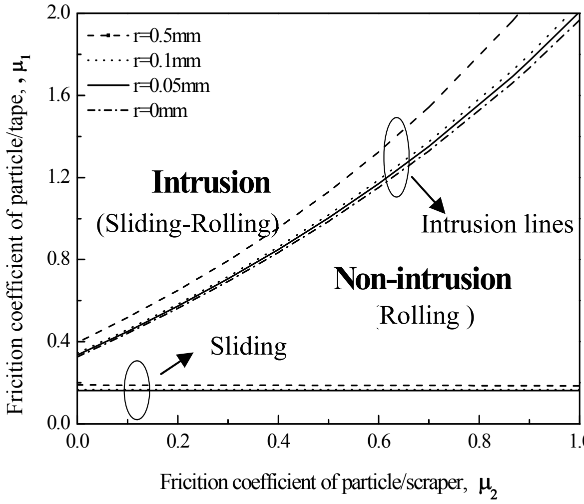


Fig.9 Intrusion pattern map of sphere particle into a contact interface

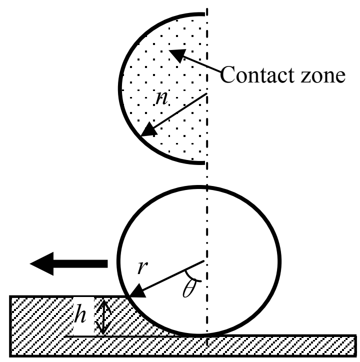


Fig.10 Contact model between hard sphere particle and polymer tape[2)]

In the case of plastic contact, the contact pressure was treated as the hardness of the softer surface, H_{tape}. Then, we have

$$\frac{w}{H_{tape}} = \frac{\pi n^2}{2} \quad (10)$$

where w is applied force and H_{tape} is the hardness of tape.

The penetration degree is calculated with parameters of particle radius, R, applied load, w, and the hardness of polymer tape, H_{tape} , by following equation:

$$D_p = \frac{h}{n} = \frac{r}{n} - (\frac{r^2}{n^2} - 1)^{1/2} = r(\frac{\pi H_{tape}}{2w})^{1/2} - (\frac{\pi H_{tape}}{2w}r^2 - 1)^{1/2} \quad (11)$$

Theoretical analysis of abrasive wear models are made by Challen and Oxley[4)] with the slip-line theory, and the determination condition and the friction coefficient for each model are both expressed as function of the attacking angle θ and the parameter f (defined as the non-dimensional value of contact shear stress divided by bulk shear stress). So the theory about abrasive wear models can be used in our case with the

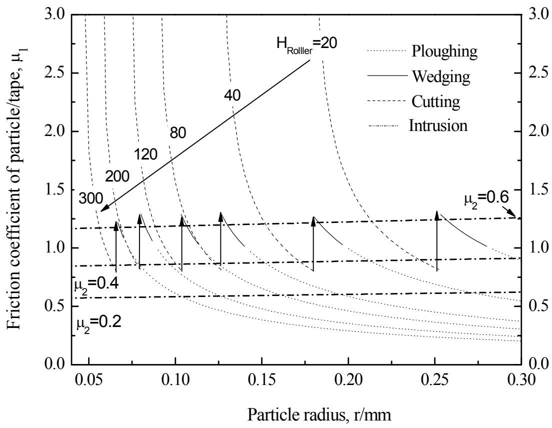


Fig.11 Intrusion conditions corresponding with abrasive wear models of different H_{tape}. (w =1 N ; f = 0.2)

introduction of equations (10) and (11).

Figure 11 shows the intrusion wear mechanisms of a sphere particle into a contact interface under the conditions of r and μ_1. The intrusion conditions with three values of μ_2 and the variation of the μ_1 of three abrasive wear models with different values of H_{tape} are also given. The three abrasive wear models with definite H_{tape} are transferred from cutting, wedge forming to ploughing with the increasing of radius of the intruding particle. The critical value of μ_1 for intrusion increases with the increasing value of μ_2 and r. And the abrasive wear mechanisms with definite H_{tape} and particle radius may change when the value of μ_2 increasing to an extent. On the other hand, the limit of each wear model always corresponds with the definite critical particle radius with definite value of H_{tape}. With the increasing of the value of H_{tape}, the friction coefficient line for abrasive wear mechanisms shifts to the direction of particle radius decreasing. That means that the abrasive wear models in intrusion can be selected by changing the tape hardness in design.

5. Conlusions

The tribological problem in natural sand dust environment was proposed and the equipment for simulating the natural sand dust environment based on Multi-Venturi structure was designed for studying the problem.

The wear mechanisms of polymer tapes in sand dust environment were examined by using a roller-scraper tribosystem. It was clarified that the mean wear rate of polymer materials in the sand dust environment was above 500 times of that in the clean air environment.

In order to control the particle intrusion into a contact interface, the mechanism of sphere particle into the contact interface was analyzed and as the conclusion, the wear mechanisms were mapped corresponding with the critical intrusion condition.

6. Aknowledgement

The authors would like to thank the Mechanical Engineering Research Laboratory of Hitachi for their support. The authors would like to thank the National High-Tech Research & Develop Plan under Grant Number 2007AA04Z307 and the National Nature Science Foundation of China under Grant Number 50775173 for their support.

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