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On the Geometrical Shape of Scratched Groove in Friction Process*

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The shape and the size of a scratched groove formed on metal surface by a single point slider, such as a cone and a sphere, have been measured in order to obtain an information for evaluating the friction force in scratching process. A special viewpoint of this study is to know the magnitude of the height of a raised ridge formed around the slider. The heights of front and side ridges were examined precisely on the scratched groove, and the effects of the cone angle and the radius of sphere on the ridge heights were well discussed.

It was found that the change in shape of the slider due to metallic transfer would have an effect on the change of the ridge height. Furthermore, it became clear that the friction force increased with increasing the height of front ridge and the groove depth.

1. Introduction

To determine the friction force in scratching process, the shape and the size of the scratching tool, and also of the scratched groove formed on metal surface are of major importance. Scratch or abrasion behavior has been studied in the fields of cutting, grinding, scratch hardness and abrasive wear^{(1)~(4)}, but the relationship of the groove dimension to the friction force has not been well investigated.

In the present study, the groove shape was examined in detail where the metal surfaces were scratched by conical and spherical sliders at low sliding speed when there was no metal removal from the surface in the form of chip. The height of raised ridge formed around the slider, as well as the depth and the width of groove, was measured for some combinations of slider and surface materials in either case where metal transfer to the slider from the surface took place or not. The effect of the height of ridge in front of the slider on the friction force was specially discussed.

2. Scratch experiment

2.1 Slider and flat specimen

Conical and spherical sliders were used in the scratch test. Materials of slider and their properties are specified in Table 1. The radius of curvature of the cone tip ranges from 2 to 6 μ . Flat specimens on which the scratched groove is formed by the slider are listed in Table 2. These materials are softer than the slider ones. H_v shown in Tables 1 and 2 denotes

Micro-Vickers Hardness with a testing load in kg in parentheses.

2.2 Scratch test

A scratch test was carried out using a friction measuring apparatus reported in the previous paper⁽⁵⁾. The friction force can be determined by mounting the slider on a suitable calibrated leaf spring and by measuring its deflection. The slider is pressed under the load against the surface of a flat specimen mounted on a sliding table which can be moved unidirectionally at selected constant speed, and then a straight scratched groove is formed on the flat surface. The sliding speed was taken from 3.57 up to 9000 μ /sec and the normal load below 1300g was applied at contact point. The experiments were carried out under lubricated and unlubricated conditions.

The size and the shape of groove were measured by Talysurf 4 profilometer.

Table 1 Specifications of slider

Material	Shape	Dimension	Hardness $H_v(0.01)$	Surface preparation
Diamond	Cone	Cone angle : $105.7^\circ \sim 162.2^\circ$		Polishing
	Sphere	Radius of curvature : 0.2 mm		
Low carbon steel (SS41)	Cone	Cone angle : $100^\circ \sim 160^\circ$	280.2	Turning
Bearing steel	Sphere	Radius of curvature : 0.25 mm		Polishing

Table 2 Specifications of flat specimen

Specimen	Material	Hardness $H_v(0.1)$	Surface roughness μR_{max}	Surface preparation
Low carbon steel	S25C	220	0.2 ~ 0.6	Grinding
	SS41	244	0.1 ~ 0.4	Polishing
Copper	CuB2	108	0.2 ~ 0.6	Grinding
	CuB2	118	0.1 ~ 0.4	Polishing
Aluminum	AlB3	40	0.8 ~ 4.0	Grinding
	A2B1	92	0.1 ~ 0.4	Polishing

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3. Results and discussion

3.1 Shape of scratched groove

The plastic deformations of the metal surface scratched by the conical and the spherical sliders are shown schematically in Figs.1 and 2 respectively. The raised ridge is formed around the slider during sliding and the front ridge, which means here a ridge observed in front of the slider, is generally higher than the side ridge, namely the ridge on the sides of the groove formed after sliding.

In both figures, W is the normal load, D the width of groove, u_1 the penetrating depth of slider and u_2 is the height of side ridge. The depth of groove u is equal to the sum of u_1 and u_2 . And also ($u_2 + u'$) denotes the height of front ridge.

The following height ratios are defined. The first is the height ratio of front ridge:

$$k = u'/u \quad (1)$$

Height ratio of front ridge : $k = u'/u$
Height ratio of side ridge : $\gamma = u_2/u_1$

Fig.1 Schematic diagram of scratched groove formed by conical slider

Height ratio of front ridge : $k = u'/u$
Height ratio of side ridge : $\gamma = u_2/u_1$

Fig.2 Schematic diagram of scratched groove formed by spherical slider

The second is the height ratio of side ridge:

$$\gamma = u_2/u_1 \quad (2)$$

An angle 2β shown in Fig.1 denotes the cone angle which is derived from the relation, $2\beta = \pi - 2\theta$, where θ is the base angle of the cone. The radius of curvature of the spherical slider is denoted as R , and α_0 is the contact angle of sphere as shown in Fig.2.

If the elastic recovery of material after scratching can be neglected, it can be assumed that the cross-section of the groove formed on the surface has a similar shape to the projected section of slider tip parallel to the sliding direction. Hence the shape and the size of groove during sliding may be estimated well by those after sliding.

A typical groove formed on a steel surface scratched by a diamond conical slider is shown in Fig.3. The height of front ridge is nearly equal to the side ridge height in Fig.3(a), but is much higher in Fig.3(b). In this experiment, there was little change in the mean height of side ridges, but the height of front ridge showed a considerable variation during sliding, probably because of instability of pile-up of material in front of the slider.

Diamond cone ($2\beta=106^\circ$)
on low carbon steel surface (S25C)
 $W = 155 \text{ g}$, $v = 3.57 \times 10^{-3} \text{ mm/sec}$

Fig.3 Shape of scratched groove formed by conical slider

(a) $2\beta = 106.0^\circ$

(b) $2\beta = 159.6^\circ$

Diamond cone on low carbon steel (S25C)

$W = 155 \text{ g}$, $v = 3.57 \times 10^{-3} \text{ mm/sec}$

Fig.4 Optical micrographs of groove formed by diamond conical slider

Metal transfer to the slider surface of diamond was not observed in the experiment shown in Fig.3. For the combination of materials where metal transfer often occurs, there is a change in shape of the slider, so that the groove shape and size will vary during scratching. In this scratching process, it is considered that the friction force and the groove dimension show an unstable variation according to the amount of transferred material; thus it may be difficult to measure the groove dimension precisely.

3.2 Scratched groove without metal transfer

3.2.1 Groove formed by the conical slider

Optical micrographs of the groove formed on the ground surface of low carbon steel (S25C) by the diamond cones are shown in Fig.4. For a large cone angle ($2\beta = 159.6^\circ$) in Fig.4(b), the ridge shows a relatively smooth profile, but the groove seems to be much deeper and the ridge contour is very confused for a small cone angle ($2\beta = 106^\circ$) in Fig.4(a). The surface of the groove is very smooth and also fragments of steel can not be observed on the surface of diamond cone after scratch test. Therefore, in these scratchings where metal transfer can be neglected, the cross-section of the groove shows a triangle shape which has the same angle as that of each conical slider.

Figure 5 shows the variations of the depth of groove u and the height of side ridge u_2 which are proportional to the penetrating depth of slider u_1 , in the scratching by diamond cone of S25C surface. Similar results were obtained in other grooves formed on each surface material shown in Table 2. Detailed discussion with respect to the groove size will be made in terms of the height ratios of ridges defined by Eqs. (1) and (2).

The height ratios of front and side ridges are plotted against the slope of

Fig.5 Relationships of height of side ridge and depth of groove to penetrating depth of slider

cone surface $\tan\theta$ for polished surfaces of low carbon steel (SS41) and copper (CuB2) as shown in Figs.6 and 7, where an experimental point shows an averaged value of more than five measurements. It is found in these figures that the height ratios are independent of the normal load, and the average height ratio of front ridge k is unaffected by the cone angle, although there is a considerable scatter. However, the height ratio of side ridge γ increases with decreasing the cone angle. The reason for this is assumed that the material can flow up very easily along the cone surface as a result of an increase in attack angle⁽¹⁾ whose minimum value is equal to the base angle of cone θ , so that it can be derived from the relation, $\theta = \pi/2 - \beta$. The result described above shows an inverse tendency to that obtained from the static indentation test of rigid wedge by Grunzweig et al.⁽⁶⁾. For 162.2° cone angle ($\tan\theta = 0.155$) of Fig.6, the height ratio γ is appreciably small in comparison with those for other small cone angles. This can be well explained by that, because of small penetrating depth of slider, the shear of metal was done only within a thin surface layer which had low friction due to metal oxide, contaminant film and work-hardening layer. In the scratching by

Fig.6 Relationships of height ratios of front and side ridges to slope of cone surface

Fig.7 Relationships of height ratios of front and side ridges to slope of cone surface

105.7° cone ($\tan\theta = 0.757$) shown in Fig.7, the height ratios k and γ decrease a little because there was some metal removal from the ridge caused by cutting.

The height ratios of ridge by the diamond conical sliders are summarized in Table 3. The height ratio of front ridge k increases in the order of SS41, CuB2 and A2B1 surfaces. This result relates to the fact that the coefficient of friction between diamond and each of these materials increases in the same order. However, the dependence of the height ratio of side ridge γ on the coefficient of friction is not obtained from Table 3.

3.2.2 Groove formed by the spherical slider

The grooves formed on CuB2 ground surface scratched by steel spheres are shown in Fig.8. It is observed that the depth of groove increases with decreasing the radius of curvature of sphere and, with an increase in the depth, the plastic deformation of the surface becomes remarkable; then the grinding mark on the surface finally disappears.

Figure 9 shows the variations of the height ratio of side ridge γ by a diamond

spherical slider with the cosine of contact angle $\cos\alpha_0$, which increases with a decrease in the groove depth. The height ratio γ becomes smaller as the depth of groove decreases, that is to say, the decrease in attack angle makes it difficult for the material to pile up at both sides of the groove. The same result was also obtained previously in the scratching by the cone. Increase of the friction coefficient causes an increase in the height ratio γ , namely in the order of low carbon steel, copper and aluminum, but this behavior has not been observed in the scratch by the cone.

The height ratio of front ridge k was obtained as shown in Fig.10 for the same experiment of Fig.9. The ratio k decreases slightly with a decreasing depth of groove for SS41 and CuB2 surfaces; but for A2B1 surface, this trend was not observed, because the evaluation of suitable value of the ratio k was difficult owing to a marked scatter of measured values.

In the case of the groove formed by the sphere, the attack angle increases gradually from bottom to ridge of the groove, and the trend of this change in attack angle becomes very conspicuous as the depth of groove increases. Furthermore, it

Table 3 Height ratio of raised ridge formed by diamond conical slider

Material of flat specimen			Height ratio of side ridge γ						Height ratio of front ridge k		
Hardness $H_V(0.1)$	$2\theta^\circ$	$\tan\theta$	SS41	CuB2	A2B1	SS41	CuB2	A2B1	SS41	CuB2	A2B1
28°	37.2	0.757	220	244	108	118	80	92	244	118	92
105.7	37.2	0.757				0.788			0.243		
122.8	28.6	0.545		0.781		0.842		0.756	0.209	0.289	0.288
142.5	18.8	0.339		0.748		0.748		0.770	0.179	0.186	0.234
162.2	8.9	0.155		0.510		0.620		0.617	0.271	0.206	0.309
106.0	37.0	0.754	0.928		0.900		0.851				
131.7	24.2	0.466	0.77								
145.0	17.5	0.315	0.74								
159.6	10.2	0.185	0.32								

Sliding direction of slider →

100 μ

Steel sphere on CuB2 surface $W = 620$ g, $v = 3.57 \times 10^{-3}$ mm/sec

Fig.8 Optical micrographs of groove formed by diamond spherical slider

Fig.9 Relationship between cosine of contact angle and height ratio of side ridge

Fig.10 Relationship between cosine of contact angle and height ratio of front ridge

is considered that the attack angle at the top of the front ridge has a significant effect on flow property of materials. So that these can be assumed to be major causes that the height ratios of ridge increases, as shown in Figs.9 and 10. Similar results were obtained in the scratchings of CuB2 and A2B1 surfaces by the steel sphere as shown in Fig.11.

Figures 9, 10 and 11 show that the height ratios of ridge increase with an increase in the depth of groove, namely an increase in the average value of attack angle, only for the cosine of contact surface of sphere $\cos\alpha_0$ above about 0.96. Below a $\cos\alpha_0$ of 0.96, the height ratios seem to be independent of the groove depth. This re-

sult shows that the height ratios are unaffected by the attack angle whose average value exceeds a limiting angle.

3.3 Scratched groove with metal transfer

If metal fragments adhere tightly to the surface of a slider during sliding, the shape and the size of the groove will be changed. Figure 12 is a typical groove formed on A2B1 surface scratched by an SS41 conical slider. In this case, the cross-sections of groove change obviously according to transfer of A2B1 to SS41 cone as the sliding proceeds, as shown in Fig.13. And an enormous "lump" or "crest" of material (A2B1) is observed at the end of the groove, which was not formed on the grooves by diamond sliders as shown in Figs.4 and 8. This suggests that the height ratio of front ridge becomes greater for the sliding in which metal transfer takes place.

To examine an effect of metal transfer on the shape of groove, the groove depth was measured in both slidings of diamond and SS41 cones on CuB2 surface as shown in Fig.14. The depth of groove by diamond cone is in proportion to the slope of cone surface $\tan\theta$, but, by SS41 cone, not always so. In particular, it is found that the depths of groove formed by 100° SS41 cone ($\tan\theta = 0.839$) under 304g loading vary according to metal transfer. Thus the effect of metal transfer on the shape and size of groove can not be neglected in practice.

Fig.11 Relationships of height ratios of front and side ridges to cosine of contact angle

Fig.12 Optical micrograph of groove formed by low carbon steel conical slider

Fig.13 Change in cross-section of groove formed by low carbon steel conical slider

Fig.14 Relationship between slope of cone surface and depth of groove

Figures 15 and 16 show the relationship between the slope of cone surface $\tan\theta$ and the height ratio of side ridge γ in the scratching of CuB2 and A2B1 surfaces by SS41 cone respectively. The height ratios γ have a considerable spread but their average values are independent of the cone angle, unlike the results obtained in the scratching by diamond cone as shown in Table 3. A similar result was observed for the height ratio of front ridge k of the groove on CuB2 surface scratched by SS41 cone as shown in Fig. 17. It is noticed that the height ratio k increases with the load. The growth of real contact area due to an increase in normal load causes an increase in the amounts of transferred material onto the cone surface; then as a result, the friction between similar metals will be dominant. This may make the friction coefficient and the height ratio of front ridge k increase.

The average values of the height ratios shown in Figs. 15, 16 and 17 and the results of another experiment which was done between SS41 cone and CuB2 surface under lubricated condition using machine oil (#120) are listed in Table 4.

Comparing the result of Table 4 with that shown in Table 3, the height ratio of side ridge γ is of the same order in both cases, but the height ratio of front ridge k by SS41 cone is greater than that by diamond cone. Therefore it can be concluded that the increase in friction due to adhe-

sion influenced mainly the formation of the front ridge.

It is noted that, for the sliding of SS41 cone on CuB2 surface in Table 4, the height ratio of front ridge k under lubricated condition is greater than that under unlubricated condition. In the present experiments, the observed amount of metallic pick-up did not differ appreciably between dry and wet conditions and the coefficient of friction in wet sliding was rather high. This phenomenon has not been clarified in the present study and further discussion will be necessary.

3.4 Relationship between the friction force and the geometry of scratched groove

The friction force in scratching is affected directly by the geometric shape of the groove formed on metal surface. Figure 18 shows the variations of the friction force and various factors which express the geometry of the groove with sliding distance for the sliding of SS41 cone on A2B1 polished surface. There was metal transfer in this experiment. In Fig. 18, the friction force F varies as the tangential projected area A_t which is equal to the cross-sectional area of the groove, but, during the former half period of this sliding, the change of the friction force does not correspond to the changes in other shape factors, namely the depth of groove u , the width of groove D and the normal projected

Fig. 15 Relationship between slope of cone surface and height ratio of side ridge

Fig. 16 Relationship between slope of cone surface and height ratio of side ridge

Table 4 Height ratio of raised ridge formed by low carbon steel conical slider

Material of flat specimen			Height ratio of side ridge γ			Height ratio of front ridge k		
Surface condition			A2B1	CuB2	CuB2	CuB2	CuB2	CuB2
$2\beta^\circ$	θ°	$\tan\theta$	Dry	Dry	Wet	Dry	Wet	
100	40	0.839	0.780	0.735	0.739	0.727	1.263	
120	30	0.577	0.591	0.647	0.742	1.076	0.507	
140	20	0.364	0.525	0.600	0.747	0.963	1.264	
160	10	0.176	0.637	0.644	0.819	0.484	1.163

Fig. 17 Relationship between slope of cone surface and height ratio of front ridge

area A_n which can be roughly estimated as follows : $A_n = 0.5\pi(D/2)^2$.

The friction force should be decided essentially by the instantaneous geometry of the groove during sliding. But the flow behavior of material around the slider is very complicated and the shape of the groove during sliding seems to differ from that after sliding. Therefore it is difficult to estimate the friction force by means of the groove geometry after sliding.

For combination of materials of Fig.18, metal transfer is very marked, so it may be difficult to obtain an interdependence between the geometry of groove and the friction force since the flow of material is not always continuous on the slider surface. Figures 19 and 20 show the relationship of the friction coefficient to the groove width in the sliding of diamond cone on CuB2 surface where metal transfer can be neglected. The friction force changes de-

pending upon the groove width in Fig.19 where the coefficient of correlation between them is 0.659, but, in Fig.20, its coefficient is 0.037, that is to say, there is no correlation. Thus, even if there is no metal transfer, good correlation between the groove dimension and the friction force was rarely observed in the present experiments. The ridge contour of scratched groove is not smooth as shown in a micro-photograph of Fig.20. The reasons for this can be considered as follows : First, the sliding speed changes slightly during sliding due to elastic flexibility of the friction measuring apparatus; second, the plastic flow of material around the slider is not entirely continuous, but is different from the flow of liquid; third, the flow pressure or the shear strength of material varies with location on the surface.

Therefore, there is poor correlation between the groove geometry measured after

Fig.18 Variations of friction force and geometry of groove with sliding

Fig.19 Variations of coefficient of friction and width of groove with sliding

Fig.20 Variations of coefficient of friction and width of groove with sliding and optical micrograph of groove

sliding and instantaneous values of the friction force. But the friction force or the width of groove oscillates about a mean value as shown in Figs.19 and 20, then the average values with respect to the groove size are considered to be important variables in order to determine the friction force, and the instantaneous value should be used to estimate a fluctuation of the friction force during sliding.

3.5 Effect of the height ratio of front ridge on the coefficient of friction

It is wellknown in many investigations that the depth of groove which is the sum of the penetrating depth of slider and the height of side ridge affects the friction force. However, the height ratio of front ridge has been assumed to be zero and an effect of the front ridge on friction has not been made clear. Figure 21 shows the variation of the coefficient of friction with the height ratio of front ridge in the scratching by SS41 cone of CuB2 surface under lubricated condition. For the experimental results in this figure, both cases with and without metal transfer are involved. It is clear that the coefficient of friction increases with increasing the height ratio of front ridge k for cone angles of 140° and 160° . It is noted in general that the average included angle of asperities on the practical surface can be assumed to be above 140° . For small cone angles, such a tendency is little observed, because the height of front ridge varies widely during sliding and the instantaneous value of the height ratio k could not be measured precisely. Furthermore it is considered that the height of front ridge which has a marked influence on the resistance to motion may be less than its measur-

ed value in this experiment, since it is possible to measure the loose ridge, such as wear debris, which is not able to affect the friction force. The result shown in Fig.21 suggests that the friction force can be affected by not only the groove depth but also the height of front ridge.

4. Conclusions

An experimental investigation with respect to scratch deformation of the metal surface by a conical and a spherical slider has been carried out and the following conclusions have been obtained.

(1) For a groove formed by the conical slider without metal transfer, the height ratio of side ridge slightly increases with decreasing the cone angle, but the height ratio of front ridge is nearly constant.

(2) For a groove formed by the conical slider with metal transfer, both height ratios of ridge are independent of the cone angle, but they show wide variation during sliding. An increase in load produces an increase in the height ratio of front ridge.

(3) For a groove formed by the spherical slider without metal transfer, the height ratios of ridge increase with increasing the contact angle α_0 , but they keep constant at large groove depth (i.e. $\cos\alpha_0 < 0.96$).

(4) The correlation between instantaneous values of the friction force and the groove size cannot be recognized, but there is good correlation between the average values of them.

(5) The friction force increases in general with the height ratio of front ridge, in particular for the scratching by the cone which has a large cone angle above 140° .

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Fig.21 Effect of height ratio of front ridge on coefficient of friction