ON SCUFFING CONDITIONS UNDER ROLLING/SLIDING CONTACT PART 3 IN THE CASE OF 0.45% CARBON STEEL QUENCHED*

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Using a two-disc machine scuffing conditions were investigated with a 0.45% carbon steel quenched which had high surface hardness and low ability to form oxide film compared with an annealed or a refined carbon steel reported in the previous papers. The following results were obtained.

(1) It was confirmed that there were three critical surface temperatures with respect to incipient scuffing. In order to prevent scuffing at each critical temperature the film parameter must be kept above a certain value according to the operating condition represented by the product of the load and the sliding speed.

(2) When the film parameter became below unity, the formation of oxide film effective in decreasing the coefficient of friction and enhancing the scuffing resistance was promoted unless scuffing took place.

(3) The rotational ratio of a high speed disc to the mating low speed disc, integral or hunting, also affected EHL film formation and scuffing resistance.

Key Words : Elastohydrodynamic Lubrication, Scuffing, Scoring, Critical Temperature, Severity of Contact, Surface Strength

1. Introduction

In the previous papers^{1,2}, the scuffing conditions in rolling and sliding contact were examined using a two-disc machine with a 0.45% carbon steel annealed or refined. The following three factors are considered the most important factors for investigating the scuffing conditions, that is, (1) surface temperature, (2) severity of contact, and (3) surface strength or surface resistance to scuffing. The bulk surface temperature is a significant factor in scuffing under the present testing condition, where the ratio of the time during which the surfaces are in contact to the time during which they are out of contact is very small. The film parameter, the ratio of the EHL film thickness to the composite surface roughness, and the surface hardness taking account of work-hardening during the run could be employed as the measures of the severity of contact and the surface strength, respectively.

In this paper the scuffing conditions in rolling and sliding contact were also examined with a 0.45% carbon steel quenched of high surface hardness using a two-disc machine. Unlike the annealed or the refined disc examined in the previous papers, the surface roughness of the quenched discs scarcely reduced and the surface hardness inversely decreased with increasing the surface temperature during the run as the load increased³.

2. Experimental Method

The disc machine previously described was used¹. The high speed disc was run at a speed of 4500 rpm, the corresponding peripheral speed being 14.1 m/s. The peripheral speed of the low speed disc was changed by using several reduction gear sets. The sliding speeds employed in the present tests were 5.0 (gear ratio $z=34/22$), 5.9 ($z=36/21$), 6.9 ($z=47/24$), and 7.1 ($z=48/24=2/1$) m/s.

The disc material was a 0.45% carbon steel quenched, of which the surface hardness ranged from 590 to 770 in Vickers hardness. The test discs had an outer diameter of 60 mm, an inner diameter of 40 mm and a contact width of 10 mm. The surfaces of the discs were finished by cylindrical grinding or buffing after grinding. The values of the centerline average roughness ranged from 0.02 to 1.8 μm . The discs with similar surface roughness and surface hardness were mated in the scuffing tests.

The lubricant used was a paraffinic base oil P500, which had viscosities at 37.8 and 98.8 °C of 98.3 and 11.1 cSt respectively. Oil was supplied to the entrance side of the rolling discs by drip feed at a rate of 15 cm^3/s in tests at a sliding speed of 5.0 m/s and at a rate of 3.3 cm^3/s in tests at the other sliding speeds. The oil temperature was controlled at 55 °C.

The scuffing tests were conducted by increasing the load from 49 kN/m (maximum Hertzian contact pressure 343 MPa) or 98 kN/m (485 MPa) in steps of 25 kN/m or 49 kN/m until a scuffing occurred. A pair of discs were run for 25 min under each load. In tests at a sliding speed of 5.9 m/s scuffing tests were also carried out under constant load conditions.

During a run the change in the contact condition between the disc surfaces

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was monitored by applying an open circuit potential difference of 100 mV between the discs as shown in Fig.1. The degree of separation R was defined by $R=E/100$, where E was a voltage difference in mV between the discs measured by the pen recorder in the circuit. The value of R was also varied with the magnitude of the parallel resistance R_2 . The changes in R with resistance R_2 are shown in Fig.2. Figure 3 shows examples of the changes in R with R varied from 500 Ω to 5 Ω . Therefore, the resistance measuring method shown in Fig.1 can estimate not only the extent of the breakdown of EHL film with high resistance but also the extent of the formation of the surface films with lower electric resistance. In the present tests 500 Ω was mainly employed as the value of R_2 .

3. Results and Discussion

3.1 Results

Under the present testing conditions the product of the applied load per unit contact width P kN/m and the sliding speed V m/s at scuffing, (PV) s kN/s, can be considered a measure of the scuffing resistance of discs. Figure 4 shows the effect of the surface roughness on the scuffing resistance. The values of the surface roughness are represented as the

Fig.1 Electrical circuit for the measurement of contacting condition

Fig.2 Effect of the parallel resistance on the degree of separation

Fig.3 Changes in the degree of separation with the varied parallel resistance

sum of roughness of high and low speed discs in centerline average roughness. Since the scuffing resistance of discs was also influenced by the surface hardness, the results were summarized with the initial surface hardness $(Hv)_0$ as shown in Fig.4, that is, discs with $(Hv)_0 = 700-730$ (hereafter referred to as $(Hv)_0 = 715$), $(Hv)_0 = 650-680$ (675) and $(Hv)_0 = 590-610$ (600). The value of surface roughness in the figure is the initial value at the scuffing load step, $(\Sigma Ra)_s$.

The scuffing loads increased with decreasing the surface hardness. In addition the scuffing loads showed duality³⁵⁶, i.e. low and high scuffing limits were obtained. The discs scuffed at the high scuffing limit always had oxide films formed on their rubbing surfaces. As shown in Fig.4 (b), all the discs in the constant load test conducted without any running-in process were scuffed at the low scuffing limit. With the discs of $(Hv)_0 = 600$ in tests at a sliding speed of 6.9 m/s, a scuffing always occurred at the

Fig.4 Effect of surface roughness on scuffing resistance
 ↑: not scuffed
 ▲: constant load test
 ○, △, □: stepping-up load test

low scuffing limit. This appears to be attributed to the poor running-in in light load steps due to severe operating condition, that is, low surface hardness and high sliding speed. In the present tests the discs with higher surface hardness had higher scuffing loads.

3.2 Surface temperature at scuffing

The surface temperature (bulk temperature) at scuffing θ_s is plotted against $(\Sigma Ra)_s$ in Fig.5. With discs of $(Hv)_0=715$ and $(\Sigma Ra)_s < 1.5 \mu m$, scuffing occurred at or above the second critical temperature θ_2 of about 190 °C in most cases. The second critical temperature of the quenched discs was slightly higher than that of the annealed or refined discs of about 180 °C. The difference in disc property may be responsible for this difference in scuffing resistance. The scuffing temperature for all the discs scuffed at the low scuffing limit in stepping-up load tests was about θ_2 . Discs not scuffed at the low scuffing limit formed effective oxide films on their surfaces before the surface temperature rose to θ_2 . The formation of effective oxide film was used as the criteria indicating the condition for preventing scuffing at the first critical temperature or the transition temperature of about 130 °C for the annealed discs of lower surface hardness as pointed out in the previous paper¹⁸⁹. With the quenched discs of a rough surface of $\Sigma Ra=2.4 \mu m$, however, scuffing was also generated at about θ_1 of 124 °C.

With discs of $(Hv)_0=600$ at a sliding speed of 6.9 m/s all the discs scuffed at about 130 °C of θ_1 . The scuffing at θ_1 is considered to be due to low surface hardness and high sliding speed. With discs of $(Hv)_0=715$, however, even in tests

Fig.5 Surface temperature at scuffing

at 6.9 m/s a scuffing was generated at θ_2 . There were some cases where the coefficient of friction had an increasing tendency with the surface temperature in a temperature range above the third critical temperature θ_3 of 240–250 °C.

The results mentioned above indicate the presence of three critical temperatures associated with incipient scuffing, that is, when the bulk surface temperature increases up to each critical one, the discs are prone to incipient scuffing as pointed out previously¹⁸⁹. However, scuffing is not always generated at the critical temperatures. The occurrence of a scuffing is closely correlated with the severity of contact, the operating condition represented by PV, the extent of the formation of oxide film, the surface strength and so on. Therefore, comprehensive consideration is required to examine the scuffing conditions.

3.3 Frictional characteristics

Figure 6 shows the relation between the coefficient of friction f and the film parameter Λ . The coefficient of friction f increased with a decreasing or an increasing severity of contact under a partial EHL regime or $\Lambda < 2^{10}$. With the quenched disc, f was high compared with the annealed or refined disc due to the poor ability to form an effective oxide

Fig.6 Relation between film parameter and coefficient of friction

Fig.7 Relation between film parameter and increase in oxygen on disc surface

film. The coefficient of friction begins to decrease with decreasing the film parameter when the film parameter is below the critical value and a scuffing is absent⁹. The critical values are 2.5-3, 2-2.5 and less than 1 for the annealed, refined and quenched discs respectively⁹.

The coefficient of friction under a partial EHL condition is affected not only by the film parameter but also by the extent of the formation of oxide film. If the extent of oxide film formation is represented by the increase in oxygen intensity on the disc surface after testing by EPMA, ΔO , the following relation holds:

$$f = 0.0896 - 2.25 \times 10^{-5} \Delta O - 5.46 \times 10^{-2} \Lambda$$

(correlation coefficient 0.881)

The coefficient of friction decreased with increasing Λ and ΔO . In addition the film parameter or the severity of contact was closely correlated with the extent of the oxide film formation as shown in Fig.7. Especially the formation of oxide film was promoted significantly when a scuffing did not occur at a film parameter below 1.

The coefficient of friction f is plotted against the load P in Fig.8. The value of f increased with increasing P or severity of the contact condition. The value of f had a limiting value according to the operating condition, at which a scuffing occurred and otherwise f began to decrease with increasing P along the limiting line. The transition of f - P relationship defined as $df/dP < 0$ is equivalent to that indicated by $df/d\Lambda > 0$ in f - Λ characteristics as shown in Fig.6. If the surface strength is kept higher than the limiting value corresponding to the operating condition represented by PV when the contact condition becomes severe, the formation of oxide film is facilitated to result in enhancing the scuffing resistance and improving the frictional characteristics without generating a scuffing.

Figure 9 indicates the relation between the surface temperature θ and the coefficient of friction f . The scales of the ordinate and the abscissa are $\log f$ and $1/\theta$. There are two tendencies in frictional characteristics. First, f increases with an increase in θ until scuffing occurred. Second, f decreases with θ without the presence of a scuffing after f passes through the maximum. In addition, f has again a tendency to increase with θ at a temperature above the

third critical temperature of 240-250 °C.

3.4 Scuffing conditions

The following three factors are considered significant ones in scuffing under the present testing conditions, that is, the surface temperature, the severity of contact, and the surface strength. The surface hardness taking account of work-hardening during a run could be taken as the surface strength against a scuffing for the refined or annealed discs¹². By contrast, with the quenched discs the surface hardness decreased with increasing load as a result of tempering. However, f PV at scuffing, $(f$ PV)_s, or the scuffing resistance of the quenched discs was

Fig.8 Load-friction characteristics

Fig.9 Changes in coefficient of friction with surface temperature

Fig.10 Effect of film parameter and PV on scuffing at first critical temperature. $\odot$: disc with oxide surface film

closely related with an increase in oxygen or the extent of oxide film formation on the disc surfaces at scuffing as pointed out previously³. Therefore, the surface strength against scuffing could be estimated from the initial surface hardness and the state of the formation of oxide film. Whether the effective oxide film is formed or not is judged from the frictional characteristics, that is, the frictional characteristics of $df/dP < 0$ is considered to indicate the formation of an effective oxide film.

The relation among the occurrence of a scuffing, the film parameter and the severity of operating condition represented by PV is shown in Fig.10 when the surface temperature rises to the first critical temperature. With discs of $(Hv)_0 = 715$ and 675 there are limiting curves in the relation between the film parameter and PV, above which a scuffing occurs. The film parameter at scuffing increased with increasing PV or severity of the operating condition. Discs forming effective oxide films before the surface temperature rose to the first critical temperature did not generate a scuffing at the limiting curve. In contrast, the discs with $(Hv)_0 = 600$ were scuffed at the first critical temperature in all cases under the present testing conditions.

In Fig.11 the relation among the occurrence of a scuffing, the film parameter and PV is shown when the surface temperature rises to the second critical temperature θ_2 . Figure 11(a) shows the results of discs which did not form effective oxide films, and in Fig.11(b) effective oxide films were already formed on the disc surfaces before the surface temperature rose to θ_2 . The oxide film was remarkably beneficial for enhancing the scuffing resistance. With the discs not forming the oxide film a scuffing took place at θ_2 in most cases. Especially,

Fig.11 Effect of film parameter and PV on scuffing at the second critical temperature
 ●▲■:scuffed, ○△:not scuffed

even under full EHL condition of $\Lambda > 2$ a scuffing was generated in a case of large PV. With the discs having an oxide film the extent of the formation of oxide film significantly affected the scuffing resistance as pointed out previously³. In Fig.11(b) there is also a limiting curve in the relation between Δ and PV, above which a scuffing takes place. It is a necessary condition for preventing a scuffing that the film parameter is kept above a certain value according to the operating condition.

3.5 Effect of rotating ratio

When the rotating ratio of a high and a low speed disc is integral such as 1/1 or 2/1, the same parts of both the disc surfaces contact repeatedly. Consequently, the formation of EHL film was facilitated as a result of improving the microgeometrical conformity between the disc surfaces as pointed out by Ichimaru¹² and Ishibashi¹³. Although the improvement in the formation of EHL film enhanced the pitting life^{12,13}, the improvement is also considered to affect adversely the scuffing resistance due to the reduction in surface roughness and the formation of surface film during the running-in process. In this paper the scuffing tests of the rotating ratios of 2/1 (integral ratio) and 47/24 (hunting ratio) were conducted to investigate the effect of the rotating ratio.

Figure 12 shows the relation between the degree of separation and the film parameter. With the integral ratio the degree of separation is large even under a partial EHL condition of $\Lambda < 2$. This means that the disc surfaces are separated by EHL film due to the improvement in the conformity of the microgeometry despite the low magnitude of the apparent film parameter Λ . The changes in the degree of separation with time are shown in Fig.13. With the discs of hunting ratio the degree of separation gradually decreased as the surface temperature increased. In contrast, with the discs of integral ratio the degree of separation had also a decreasing tendency at the initial stage of each load step, but it started to increase due to the improvement of the conformity of the microgeometry. In addition, the discs of integral ratio

Fig.12 Effect of rotating ratio (gear ratio) on degree of separation

Fig.13 Change in degree of separation with time

Fig.14 Effect of rotating ratio on scuffing resistance

generated a scuffing in most cases when the degree of separation fell to 0. On the other hand the discs of hunting ratio did not generate a scuffing when the degree of separation fell to 0. With the discs of hunting ratio the contact parts of the mating discs were irregularly changed so that mildly scuffed areas are unlikely to develop into a scuffing. Besides, the hunting ratio discs were promoted the formation of oxide film and increased the surface strength against scuffing in light load steps owing to their high severity of contact condition compared with the corresponding discs of integral ratio. The results of EPMA indicated the superiority of the hunting ratio discs in the formation of oxide film. Therefore the hunting ratio discs had to some extent higher scuffing loads than the integral ratio discs shown in Fig.14.

However, as Ichimaru already pointed out¹², the effect of the rotating ratio on the scuffing resistance is affected by the operating condition, the direction of roughness and so on. Further elucidation will be required.

4. Conclusions

Scuffing conditions were examined in rolling/sliding contact using a 0.45% carbon steel quenched. The following

results were obtained.

- (1) It was confirmed that there were three critical surface temperatures associated with incipient scuffing.
- (2) The surface temperature, the severity of contact, and the surface strength were closely correlated with each other in the process of a scuffing. There was a limiting curve at each critical temperature in the relation between the film parameter and the product of the load applied and the sliding speed, above which a scuffing took place.
- (3) When the film parameter became below unity, the formation of an effective oxide film which decreases the coefficient of friction and increases the scuffing resistance was promoted unless a scuffing took place.
- (4) The rotating ratio of the high speed disc to the low speed one, integral or hunting, also affected the EHL film formation, the state of the formation of the oxide film and the scuffing resistance.

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