531.46:539.375

Paper No. 199-15

On Scuffing Conditions Under Rolling/Sliding Contact Part 1 In the case of annealed 0.45 % carbon steel*

By Yuji YAMAMOTO**

Using a two disc machine, conditions to give rise to scuffing or to prevent scuffing were investigated with 0.45 % carbon steel annealed which has much ability to be work-hardened. Following three factors were considered to be most important associated with the occurrence of scuffing, that is, bulk surface temperature, severity of contact, and surface resistance to scuffing. Three different critical conditions of surface temperature related to scuffing should be taken account of. The first one is the transition temperature, the second one is about 180 °C at which the composition of oxide films formed on the disc surfaces seems to be changed, and the third one is about 240 °C at which black surface films begin to be formed.

The severity of contact could be represented by dimensionless film thickness. The surface strength could be expressed by the surface hardness taking account of work-hardening during testing, which is always accompanied by the formation of oxide film. The existence of critical surface strength according to operating conditions, above which there is little chance of scuffing, is confirmed.

1. Introduction

There are many machines operating under rolling/sliding contact conditions such as gear, cam and follow, and friction wheel. Once scuffing occurs in the machine elements, the damages tend to develop rapidly into catastrophic ones, so that studies on scuffing were so far made by many investigators.⁽¹⁾ To investigate scuffing conditions it is necessary to consider comprehensively the effects of many factors such as load, sliding speed, surface roughness, surface hardness, surface temperature, and extent of formation of surface film. The condition for the occurrence of scuffing, therefore, does not appear to be able to be explained by a simple criterion because of the complicated phenomena involved.⁽²⁾

In this paper scuffing conditions under rolling/sliding contact were investigated using a two disc machine with annealed carbon steel of high ability to be work-hardened. Following three factors are considered to be most important to investigate the scuffing conditions, that is, (1) surface temperature, (2) severity of contact, and (3) surface strength or surface resistance to scuffing. The surface strength should be determined by taking account of surface hardness, surface roughness, extent of surface film formed on disc surfaces, and so on.

As pointed out previously there are three critical values of surface temperature associated with the occurrence of scuffing.⁽³⁾ The first one is a transition temperature

whose value is influenced by disc material, oil, and other operating conditions. The second one is about 180 °C at which the oil attaching to disc surfaces begins to be oxidized markedly, and at the same time the composition of the oxide films formed on the surfaces seems to be changed.⁽⁴⁾ The third one is about 240 °C at which a black surface film begins to be formed. The bulk surface temperature is considered to be essential rather than the maximum contact temperature including a component of flash temperature to estimate the occurrence of scuffing in the case where the contact time (on time) of disc surfaces is remarkably short compared with the non-contact time (off time), on/off ratio being below 1/250 under this test conditions. Surface damages suffered at the contact area as a result of an increase in the maximum surface temperature above the critical temperature is considered to be undone during the non-contact time much longer than the contact time if the bulk surface temperature does not exceed the critical one. Then, hereafter, the surface temperature means the bulk surface temperature.

However, as pointed out by Fujita et al.⁽⁵⁾ in the case such as a four ball testing machine where on/off ratio is about unity, the maximum surface temperature must be taken into consideration since the surface damage may not be undone during the non-contact time.

It is considered that dimensionless film thickness or film parameter Λ defined by a ratio of EHL film thickness h_0 to composite surface roughness σ , $\Lambda = h_0/\sigma$, can be a measure of the extent of severity of contact. It was already confirmed in another scuffing test using a two disc machine that the scuffing resistance represented by the product of scuffing load and sliding speed increases with an increase in the surface hardness, $(H_v)_s$, measured immediately before scuffing,

* Received 6th October, 1980.

** Professor, Faculty of Engineering, Kyushu University, 6-10-1, Hakozaki, Higashi-ku, Fukuoka.

which includes an increase due to work-hardening during test.⁽⁶⁾ Therefore, it seems to be reasonable that the surface hardness of the discs taking account of work-hardening during testing is adopted as a criterion of the surface strength related to scuffing.

Furthermore, the scuffing resistance of oils of identical viscosity is influenced by a difference in the molecular weight distribution.⁽⁷⁾ Thus, mineral oils with narrow ranged molecular weight distribution were used as lubricants in this investigation.

2. Experimental

The two disc machine used was the same one as used in the previous investigation.⁽⁸⁾ The higher speed disc was kept at a constant rotating speed of 75 s^{-1} , 4500 rpm, the corresponding peripheral speed being 14 m/s. The lower speed disc was driven through reduction gears. The sliding speeds adopted were 4, 5, and 5.9 m/s.

The disc material was 0.45 % carbon steel annealed with high ability to be work-hardened, the surface hardness of which ranged from 169 to 186 Hv. The sizes of the discs were 60 mm outer diameter, 40 mm inner diameter, and 10 mm contact width. The disc surfaces were finished by cylindrical grinding, the values of the surface roughness in centerline average being changed from 0.27 to 0.32 μm .

Paraffinic base oils of narrow ranged molecular weight distribution were used as lubricants. The properties of the oils are

shown in Table 1. The oil was supplied to the entrance side of the contact areas of the discs by drip feed at a rate of $3.3 \text{ cm}^3/\text{s}$ with sliding speed of 4 and 5.9 m/s, or $15 \text{ cm}^3/\text{s}$ with sliding speed of 5 m/s. The oil temperature was kept at 55°C .

Each test was conducted by increasing the load from 98 kN/m, the corresponding Hertzian contact pressure being 485 MN/m^2 , in steps of 49 kN/m. A pair of discs were run for 25 min under each load. If scuffing did not occur, the load was raised to the next step. The coefficient of friction during testing was measured except in a few cases, and after each test the surface temperature, surface hardness, and the surface roughness were measured.

3. Relation between formation of oxide film and dimensionless film thickness or surface temperature

Fig.1 shows a relation between the dimensionless film thickness Λ and the coefficient of friction f at the end of each test step, where EHL film thickness was calculated using Dowson equation.⁽⁹⁾ With the tests at sliding speed of 4 m/s, f increased with a decrease in Λ in light load stages, but when Λ decreased below about 3, f began inversely to decrease with a decrease in Λ . This suggests that a decrease in f with a decrease in Λ in the range of Λ below about 3 is considered to result from the formation of a beneficial oxide film^(4,7) which is promoted by plastic deformation of the disc surface⁽¹⁰⁾ which is

Table 1 Properties of lubricants

Oil	Density	Viscosity, 10 ⁻⁶ m ² /s(cSt)		Mean Molecular Weight	Ring Analysis, %			Sulfur content wt %	Viscosity Index
	15/4°C	37.8°C	98.9°C		C _A	C _N	C _P		
P60	0.8634	7.8	2.2	264	9.4	35.0	55.6	0.01	84
P150	0.8618	32.2	5.3	400	0.0	33.4	66.6	0.00	103
P500	0.8670	98.3	11.1	539	0.0	29.2	70.8	0.00	108
BS *	0.8840	467	32.0	741	3.7	24.2	72.1	0.01	109

* BS : Bright Stock

Fig.1 Relationship between dimensionless film thickness and coefficient of friction, S:scuffing, LS:light scuffing, $\circ$:P60 $\triangle$:P150 $\bullet$:P500 $\blacktriangle$:BS

facilitated by an increased extent of direct contact.

In tests at sliding speed of 5.9 m/s with high viscosity oils, P500 and BS, the change in f with Λ is similar to that at sliding speed 4 m/s. With low viscosity oils, P60 and P150, however, f does not decrease with a decrease of Λ , but remains a high value even in the range of Λ below about 3. The reason seems to be in the test condition that, due to the high sliding speed and thin EHL film build-up caused by the low viscosity, the lubricating condition is severe even at an initial load step 98 kN/m, so that the formation of beneficial oxide film and improvement in the surface roughness may not be sufficient in the running-in process of initial low load steps.

The coefficient of friction f at the end of each step is plotted against the corresponding surface temperature θ in Fig.2. The scales of the ordinate and the abscissa are $\log f$ and the reciprocal of absolute temperature respectively. If scuffing does not occur in a low surface temperature range, a decrease in f with an increase in θ was observed even under condition of Λ above about 3. Since the tests were conducted at constant sliding speeds by increasing the load, θ increases and Λ decreases with load. Therefore, the advantageous condition of $\partial f / \partial P < 0$, that is, $\partial f / \partial \theta < 0$ or $\partial f / \partial \Lambda > 0$, where P is load, is realized at a higher load if the discs do not scuff in low load steps.

The critical temperature above which f begins to decrease with surface temperature even when the contact condition appears to be mild, or Λ is kept above 3, is a transition temperature or the first critical temperature θ_1 as mentioned in "Introduction". The transition temperature means a mechanical transition temperature at which the coefficient of friction begins to increase abruptly as the result of thermal disturbance and mechanical disturbance caused by rubbing surfaces.⁽¹¹⁾ The value of θ_1 is affected by many factors such as oil, disc material, applied load, sliding speed, and so on.⁽¹⁴⁾

In Fig.3 the surface hardness (Hv)s measured immediately before scuffing in the cases where scuffing is considered to take place at θ_1 , that is, Λ was kept above about 3 and a beneficial oxide film was not formed in load steps prior to the occurrence of scuffing. This suggests that θ_1 increases proportionally to the surface strength. If the discs did not scuff at θ_1 , beneficial oxide films begin to be formed even when Λ is kept above about 3, so that f decreases with an increase in the surface temperature.

Therefore, the conditions for the for-

(a) sliding speed 4m/s

(b) sliding speed 5.9 m/s

Fig.2 Relation between surface temperature and Coefficient of friction, S:scuffing
○ :P60 △ :P150 ● :P500 ▲ :BS

Fig.3 Increase in surface temperature at scuffing with surface hardness in cases of discs without beneficial oxide films, ● :P500 ▲ :BS

mation of the beneficial oxide film are considered as follows. Firstly Λ decreases below about 3 before the surface temperature reaches the transition temperature. Secondly the degree of the contact is held mild by keeping Λ high even at the surface temperature above the transition one at which the ability of the oil to adsorb the disc surface is considered to disappear.

4. Relation between scuffing resistance and surface hardness

It was already confirmed that the product of scuffing load and sliding speed at scuffing, (PV)s, representing a criterion of the scuffing resistance increases with an increase in the surface hardness (Hv)s immediately before scuffing.⁽⁶⁾ The increase in the surface hardness based on work-hardening during testing is more favourable than that resulting from a change in heat treatment or carbon content. The advantage of the increase in surface hardness based on work-hardening comes from the fact that oxide film formation is inevitably accompanied by an increase in surface hardness, so that the disc surface is strengthened by both of them. It was confirmed that oxygen concentration on the disc surfaces increases proportionally to an increase in the surface hardness during testing.

Fig.4 shows the relation between (PV)s and (Hv)s of the discs whose initial surface hardness and initial surface roughness were nearly equal, that is, they were Hv=174~182 and Ra=0.27~0.32 μ m respectively. * in the figure means the occurrence of scuffing at the third critical temperature θ_3 , and † indicates that scuffing does not occur. There is a close correlation between (PV)s and (Hv)s except in the result marked with *. An empirical formula can be written as

$$(PV)s = 0.0335(Hv)s - 4.90$$

$$r = 0.980 \quad (1)$$

where r is the coefficient of correlation and units of (PV)s and (Hv)s are MN/s and Vickers hardness respectively. A critical surface hardness (Hv)c for the occurrence of scuffing exists depending on the test condition. Scuffing does not seem to occur when the surface hardness exceeds the critical one. The critical surface hardness is given from Eq.(1) as follows:

$$(Hv)c = 146.3 + 29.9 PV \quad (2)$$

where units of (Hv)c and PV are Vickers hardness and MN/s, and P and V are load per contact width and sliding speed at each test.

In this experiment scuffing did not take place when $\Delta H = (Hv)b - (Hv)c$ was held above 6, where (Hv)b is the initial surface hardness at each load step. However, scuffing does not always occur if ΔH is negative. The occurrence of scuffing is strongly associated with the surface temperature and the severity of contact as well as the surface hardness. The changes in the surface hardness with load are shown in Fig.5. A straight line in Fig.5 expresses the relation according to Eq.(2). With the oil BS a scuffing does not occur because the surface hardness always exceeds the critical value, and with P60 a scuffing takes place when the surface hardness reaches the critical value. On the other hand, with P500 a scuffing does not occur even when ΔH becomes negative. This suggests that

it is not a sufficient but a necessary condition for the occurrence of scuffing that the surface hardness or the surface strength decreases to the critical value.

5. Condition for occurrence of scuffing

There are three critical temperatures related to the occurrence of scuffing. Scuffing did not occur below the first critical one θ_1 in this experiment. In the cases where a scuffing took place at θ_1 , the dimensionless film thickness Λ was held above about 3 and beneficial oxide film was

Fig.4 Relation between scuffing resistance (PV)s and surface hardness immediately before scuffing, *:scuffing at third critical temperature, †:not scuffing,

Fig.5 Changes in surface hardness during tests, S:scuffing
Lubricant(Sliding speed, m/s)
○ :P60(5.9) △ :P150(4) ▲ :BS(4)

not formed on the disc surface in load steps before scuffing load except in the case of P60 at sliding speed 5.9 m/s as mentioned later.

In Fig.6 with P500 at sliding speed of 5m/s, θ_1 near 130 °C, the change in Λ and the surface temperature θ with load are shown. With the discs scuffing at θ_1 , Λ was kept always above about 3 at load steps before the scuffing load and a scuffing occurred as soon as the surface temperature reached θ_1 (O in Fig.6), Λ at the scuffing being 1.9. In the other case (● in Fig.6), however, Λ decreased already below 2.5 before θ reached θ_1 . For example Λ and θ at a load of 245 kN/m were 1.47 and 120 °C respectively. In this case a scuffing did not occur although θ exceeded θ_1 and the contact condition became severe at load steps above 294 kN/m.

The results of BS at sliding speed of 4 m/s are shown in Fig.7. LS in the figure means light scuffing, that is, scuffed parts were limited area and scuffing was not progressive so that the scuffing test could be continued. In one case (O in Fig.7) where Λ was always kept above about 3 until the surface temperature reached θ_1 of nearly 130 °C, a scuffing occurred at θ_1 despite a large value of $\Lambda = 4.6$ at a load of 245 kN/m. However, the surface damage remained insignificant, that is, light scuffing, owing to the mild degree of contact as a result of keeping Λ high, although the surface hardness was not sufficiently high to prevent scuffing, ΔH being 4.8. The formation of oxide films in this case is not fully facilitated due to deficiency in severity of contact compared with the case of Λ decreasing below about 3. Therefore, when Λ decreased to 2 and direct contact parts began to support the load in place of the EHL film built up based on hydrodynamic action of oil,⁽¹³⁾ a scuffing occurred because

Fig.6 Relation between occurrence of scuffing and changes in dimensionless film thickness and surface temperature, sliding speed 5m/s, lubricant P500, S:scuffing.

of the insufficient surface strength below the critical value. In the other case (● in Fig.7) Λ decreased already below 2.5 before θ reached θ_1 , so that beneficial oxide films were formed. Nevertheless a light scuffing took place when Λ decreased to 1 and the major parts of load was supported not by the EHL film but by the direct contact parts, the contact condition being very severe.⁽¹³⁾

Fig.7 Effect of changes in ΔH , Λ , and θ on occurrence of scuffing, sliding speed 4m/s, lubricant BS, S:scuffing LS;light scuffing

Fig.8 Relation between occurrence of scuffing and changes in Λ , ΔH , and θ . S:scuffing, sliding speed 5.9m/s
O :P60 ● :P500

The reason why the scuffing did not fully grow in spite of the high severity of contact is considered to lie in the high surface strength of $\Delta H = 8$.

Fig.8 shows some results at sliding speed of 5.9 m/s. With P500 a scuffing also occurred at θ_1 when an oxide film was not formed, ΔH and Λ at the scuffing being -1.6 and 2.3 respectively. On the other hand, with P60 Λ was below 2 even at the initial load 98 kN/s so that a beneficial oxide film was formed and then a scuffing did not occur at a surface temperature above θ_1 of nearly 60 °C. A scuffing, however, occurred at θ_1 in spite of the formation of an oxide film and Λ being held above 2, when the surface strength decreased below the critical value at a load of 294 kN/m. This is considered to result from the insufficiency of the running-in process of P60 as mentioned above, so that a scuffing occurred when the surface strength decreased to the critical value.

From the above mentioned results, it is confirmed that the discs scuff at the first critical temperature θ_1 when the following conditions are satisfied. That is, a beneficial oxide film is not formed by keeping Λ above about 3 until the surface temperature increases to θ_1 , and the surface strength is below the critical value when the surface temperature reaches θ_1 . The scuffing damage, however, tends to remain insignificant if Λ is sustained above 3 at the scuffing. This condition is not sufficient but necessary to give rise to scuffing, since even at a load step at which the final surface temperature increases to θ_1 , a scuffing is not considered to occur if an oxide film is formed in an early stage of the load step before the surface temperature increases to θ_1 .

The second critical temperature θ_2 is nearly 180 °C. In scuffing tests using a hardened carbon steel as disc material and P500 as lubricant at sliding speed of 5 m/s reported previously, almost all discs scuffed at θ_2 if a beneficial oxide film was not formed.⁽¹⁴⁾ Fig.9 shows some results with an annealed carbon steel in this experiment at sliding speed of 4 m/s. With P500 a scuffing did not occur at load 588 kN/m owing to the surface temperature being 165 °C below θ_2 , though the surface strength decreased below the critical value and the contact condition was severe, the corresponding ΔH being negative and $\Lambda = 1.4$. At the next step of 637 kN/m wherein the surface temperature reached θ_2 , the discs scuffed in spite of little difference in ΔH and Λ from those at a load of 588 kN/m. On the other hand, with BS a scuffing did not occur at 490 kN/m owing to a high value of $\Lambda = 2.3$ despite the surface

temperature increasing to θ_2 and the surface strength decreasing nearly to the critical value of $\Delta H = 1.8$. However, a scuffing occurred at a surface temperature of 181 °C with P150 at which ΔH was negative and $\Lambda = 2.0$. $\Lambda = 2$, above which the lubricating condition is considered to be in EHL regime where the major part of load applied is supported by EHL film, seems to be a critical value to prevent scuffing at θ_2 . Furthermore, as shown in Fig.7, with BS at 441 kN/m the discs did not scuff though the surface reached θ_2 and Λ was a very low value of 0.48, because the surface strength was sufficiently high compared with the critical one, ΔH at the load being 6.8.

To prevent the occurrence of a scuffing when the surface temperature increases to the second critical temperature θ_2 , it is necessary to satisfy the condition that the surface strength is kept at a sufficiently high value ($\Delta H > 6$), or the lubricating condition is maintained in EHL regime ($\Lambda > 2$). However, the discs do not always scuff unless this condition is satisfied. This is only a necessary condition to prevent scuffing. In fact there was a case where a scuffing did not take place under the condition of $\theta = 185^\circ\text{C}$, $\Delta H < 0$, and $\Lambda = 1.24$ with P500.

It was reported previously that a scuffing occurred regardless of surface temperature when Λ decreased to 1 with a hardened carbon steel at sliding speed of 5.9 m/s.⁽⁷⁾ $\Lambda = 1$ is considered to be a critical condition in this investigation with annealed carbon

Fig.9 Effects of changes in ΔH , Λ , and θ on occurrence of scuffing, sliding speed 4m/s, S:scuffing, ○:P60 ●:P500 ▲:BS

steel discs taking account of the results in Fig.7 and Fig.9. When Λ decreases to 1, there appears to be a fair chance for scuffing at any surface temperature if the surface strength is not sufficiently high above the critical value, i.e. in this investigation $\Delta H < 5$.

There was only one case in which a scuffing occurred at the third critical temperature θ_3 , but the surface strength of the discs scuffed was a significantly high value of $\Delta H = 19$. This seems to suggest the existence of another criterion for the surface strength at θ_3 . Furthermore, there were cases where a scuffing did not occur in spite of severe contact conditions of $\Delta H < 0$ and $\Lambda < 1$. This seems to require further elucidation.

6. Conclusions

Scuffing conditions under rolling/sliding contact were investigated with an annealed 0.45% carbon steel of high ability to be work-hardened using a two disc machine. The most important factors to be taken into consideration relating to scuffing are considered to be surface temperature, severity of contact, and surface strength. There are three critical temperature associated with the occurrence of a scuffing, that is, transition temperature, nearly 180 °C, and about 240 °C. In estimating the scuffing condition the bulk surface temperature not including a component of flash temperature is considered to be essential in the two disc machine tests where the contact time of the disc surfaces is much shorter than the non-contact time. The dimensionless film thickness which is a ratio of EHL film thickness to composite surface roughness is considered to represent the severity of contact. The surface hardness taking account of work-hardening during testing seems to be reasonable as a criterion of the surface strength.

It is the condition to prevent scuffing at the first critical surface temperature or the transition temperature that a beneficial oxide film is formed by decreasing Λ below about 3 until the surface temperature increases to θ_1 , or Λ is kept at a sufficient high value when the surface temperature reaches θ_1 . The latter case tends to be accompanied by the danger of light scuffing being of limited area and not being progressive. The scuffing at the second critical temperature of about 180 °C is prevented by keeping Λ above 2 or holding the surface hardness sufficiently high above the critical value.

Furthermore, $\Lambda = 1$ at which the direct contact part begins to support the major part of applied load is considered to be another critical condition to give rise to scuffing. There is a fair chance for scuffing at $\Lambda = 1$.

Acknowledgements

The author wishes to express his appreciation to Dr. F. Hirano, Emeritus Professor of Kyushu University, for his kind guidance, and also to Research Institute of Idemitsu Kosan Co. for supplying the lubricants used

in the present investigation, and to Mr. M. Hashimoto, Department of Mechanical Engineering, Kyushu University, for assistance offered during the investigation.

References

- (1) Dyson, A., Tribology International, Vol.8 (1975), p.77 and p.177.
- (2) Hirano, F. and Ueno, T., J. Japan Soc. Mech. Engrs., (in Japanese), Vol.79, No.696 (1976-11), p.1073.
- (3) Yamamoto, Y. and Hirano, F., J. Japan Soc. Lubric. Engrs., (in Japanese), Vol.19, No.3, (1973-3), p.199.
- (4) Hirano, F. et al., Proc. 6th Leeds-Lyon Symp. Thermal Effects in Tribology, Mech. Engrg. Pub. (1980), p.298.
- (5) Fujita, K. et al., Trans. Japan Soc. Mech. Engrs. (in Japanese), Vol.46, No.408 (1980-8), p.953.
- (6) Yamamoto, Y. and Hirano, F., Wear, Vol.63, No.1 (1980), p.165.
- (7) Hirano, F. and Yamamoto, Y., Proc. Tribology 1978, Swansea, Inst. Mech. Engrs. (1978), p.35.
- (8) Hirano, F. et al., Proc. 9th Tribology Convention, Isle of Man, Inst. Mech. Engrs. (1971), C85/71.
- (9) Dowson, D., Proc. Conf. Lubrication and Wear, Elastohydrodynamics, Paper 10, (1967), p.151.
- (10) Fink, M., Forshrer-Ber., VDI, Vol.5, No.7 (1967-6), p.1.
- (11) Handbook of Lubrication edited by Japan Soc. Lubric. Engrs. (in Japanese), Yokendo (1970), p.60.
- (12) Poon, S.Y. and Haines, D.J., Proc. Inst. Mech. Engrs., Vol.181, Pt.6 (1966/67), p.393.
- (13) Yamamoto, Y. et al., Bull. Japan Soc. Mech. Engrs., Vol.23, No.186 (1980) p.2132.
- (14) Fein, M. et al., Trans. ASLE, Vol.2, (1959), p.50.