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On the Effect of Metal-Structure on Scoring Limit*

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In the estimation of scoring limit of gears, it is supposed that the effect of metal-structure and hardness is important.

In the present report, the scoring limit was studied by using an Amsler wear testing machine. The materials of test rollers were steels specified under JIS S43C, SCr4 and SCM22H.

From experimental results on various metal-structures from ferrite-pearlite structure to martensite structure, it became clear that the scoring limit increases with the hardness and an initial scoring takes place on the surface of steel containing a small quantity of retained austenite.

1. Introduction

As some factors which influence on the scoring limit of gears, we can consider many factors controlling the maximum flash temperature occurring on gear surface, namely the gear surface load including the dynamic applied load, the sliding velocity, the tangential velocity and the coefficient of friction on gear surface; the thermal constants, such as thermal conductivity and specific heat, the surface roughness; the characteristics of lubricant, such as viscosity, chemical composition and existence of additive; and the micro-structure and hardness of gear surface layer.

Many test results with respect to the influences of many factors controlling the maximum flash temperature occurring on gear surface on the scoring limit or the influence of lubricant have been reported and those influences are clear to a considerable degree. However, the relation between the metal structure of gear material and the scoring limit is not much studied, and concerning these problems we can know only a few reports on the relation between the initiation of scoring¹⁾ and the transformation temperature of steel, the relation between alloy elements and the scoring limit²⁾, the influence of thermal conductivity of metal surface on the scoring limit³⁾.

However, the scoring limit of gear is affected considerably by heat treatment, so that it is important to study the relation between the scoring limit and the metal structure for estimating the scoring strength and researching the mechanism of scoring initiation. In this report the influences of the metal structure, the hardness and the coefficient of friction on the scoring

limit are studied using an Amsler type wear testing machine. Materials used in this test are S43C, SCr4 and SCM22H which are generally used as gear materials. Many kinds of heat treatment were conducted on the cylindrical test specimens.

2. Materials and experimental condition

The chemical compositions of the materials used in the present scoring test are shown in Table 1. The scoring test was conducted by two cylindrical test specimens at first, but those specimens contacted partially in the width direction and the plastic deformation occurring at the edge of specimen caused a contact such as in crowning specimens, and the contact stress consequently changed irregularly with an increase of cycles.

Therefore, we used a cask type specimen which had an axial radius of $R = 65\text{mm}$ as the upper specimen and a cylindrical one as the lower specimen. Those specimens were cut to 40 mm diameter and 10 mm width by means of a lathe. After rough grinding the heat treatments shown in Tables 2, 3 and 4 were conducted on each specimen and then the finish grinding was done. The conditions of heat treatment to study the effect of retained austenite on scoring were selected as in Table 4. The quantity of retained austenite of case hardened steel is generally affected by the quantity of carbon in the surface layer. It can be controlled by (i) the dew point, (ii) the carburizing temperature and (iii) the carburizing time. It is more easy and correct to control the quantity of carbon in surface layer by carburizing time, and this method is mainly used in this experiment.

However, to obtain 10% retained austenite, the method controlling the dew point and the carburizing temperature is used.

And X-ray diffraction method is used to measure the quantity of retained austenite.

A special grinding equipment⁴⁾ (the grain

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size of grinding wheel : A80) for cask type specimen was used to grind the cask type specimen and the cylindrical specimen was ground by an ordinary cylindrical grinder (the grain size of grinding wheel : A60). Maximum surface roughnesses of cylindrical and cask type specimens were both 1.7μ in circumferential direction, and in axial direction that of cylindrical specimen was below 4.5μ and that of cask type specimen was below 6μ .

When the specimen was quenched into water or the water contained 20% salt, the

capacity of the tank was 8 liters and the temperature of cooling media was 8°C . In the case of oil quenching, the number 200 turbine oil with temperature 14°C was used, and the tank capacity was 10 liters.

The micro-structures etched by 3% Nital were examined using an optical micro-scope and an electron microscope. And the structures were revealed as shown in Tables 2 and 3. Some examples of micro-structures are shown in Fig.1.

Test rig used for scoring test is an Amsler type wear testing machine in which load is applied by oil pressure. The applied load of the first stage is 75kg, it is kept for 15 seconds and is increased at a rate of 75kg at each stage. The frictional moment is measured at each stage.

Table 1 Chemical compositions of test materials

Shortened symbol	JIS symbol	C	Si	Mn	P	S	Ni	Cr	Mo	Cu
C	S43C	0.44	0.19	0.73	0.017	0.017	—	—	—	—
R	SCr4	0.43	0.32	0.76	0.01	0.02	0.07	1.04	—	0.11
M	SCM22H	0.19	0.28	0.80	0.01	0.02	0.07	1.16	0.20	0.13

Table 2 Heat-treatment, metal structure and surface hardness of C specimens

Specimen number	Heat-treatment	Structure	Hardness Hv (500gr)		
			Cylinder specimen	Cask specimen	Mean
C1 A B	After heating for 30min. at 800°C , slow cooling by 25°C/hr , cooling rate from 800°C to 650°C , then cooling in furnace	Spheroidal pearlite	189	211	200
			193	229	211
C2	No treatment	Ferrite-pearlite	204	207	206
C3	After heating for 2 hr. at 850°C , quenching in water After heating for 4 hr. at 620°C , cooling in water	Sorbite	263	291	277
C4 A B	After heating for 1 hr. at 900°C , cooling in blast from 850°C , followed by heating for 1 hr. at 575°C , then cooling in furnace	Mixed structure of Ferrite-Pearlite and Sorbite	255	253	254
			243	261	252
C5	After heating for 2 hr. at 850°C , cooling in air	Ferrite-Pearlite	248	253	251
C6 A B	After heating for 1 hr. at 900°C , quenching in water at 850°C , followed by heating for 1 hr. at 600°C , then cooling in furnace	Sorbite	227	250	239
			255	247	251
C7 A B	After heating for 1 hr. at 900°C , quenching in water at 850°C , followed by heating for 1 hr. at 400°C , then cooling in furnace	Troostite	371	384	378
			405	451	428
C8	After heating for 1 hr. at 900°C , quenching in oil bath, followed by heating for 1 hr. at 250°C , then cooling in air	Martensite + Retained austenite	289	303	296
C9 A B	After heating for 1 hr. at 1000°C , quenching in oil bath	Martensite + Retained austenite	251	287	269
			278	268	273
C10 A B	After heating for 1 hr. at 1000°C , quenching in oil bath, followed by heating for 1 hr. at 250°C , then cooling in air	Martensite + Retained austenite	315	321	318
			294	344	319
C11 A B	After heating for 1 hr. at 1000°C , quenching in water	Martensite + Retained austenite	572	523	548
			450	554	502
C12 A B	After heating for 1 hr. at 1000°C , quenching in water, followed by heating for 1 hr. at 250°C , then cooling in air	Martensite + Retained austenite	435	455	445
			462	554	508
C13	After heating for 1 hr. at 1000°C , quenching in 20% salt water	Martensite + Retained austenite	486	460	473
C14 A B	After heating for 1 hr. at 1000°C , quenching in 20% salt water, followed by heating for 1 hr. at 250°C , then cooling in air	Martensite + Retained austenite	459	496	478
			417	510	464
C15 A B	After heating for 1 hr. at 900°C , quenching in water at 850°C , followed by heating for 1 hr. at 250°C , then cooling in air	Martensite	652	652	652
			670	621	646
C16 A B	After heating for 1 hr. at 900°C , cooling by 100°C/hr . to 850°C and by 25°C/hr . to 750°C , then quenching in water	Martensite + Ferrite	653	628	641
			690	683	687
C17	After heating for 1 hr. at 900°C , cooling by 100°C/hr . to 850°C and by 25°C/hr . to 740°C , then quenching in water	Martensite + Ferrite	750	746	748
C18 A B	Induction hardening	Martensite	619	621	620
			660	668	664

Frictional force of test machine itself was measured and then this friction loss was taken into account in the calculation of friction force. The test speed for the C-specimen and R-specimen was speed step I shown in Table 5. As the speed step I was not so fast as to initiate scoring in M-specimen, the speed step II faster than speed step I was adopted. The lubricant used in scoring test was the number 90 turbine oil which was force-fed. The oil temperature was $18.5^{\circ}\text{C} \pm 1.5^{\circ}\text{C}$ and the quantity of oil supply was 0.8 liter per minute.

3. Test results and the investigation

3.1 Change of frictional coefficient and relation between the load of scoring limit and the metal structure

The changes of the frictional coefficient and surface roughness during the test are shown in Fig.2(a)~(e). As shown in Fig.2, the lubricating condition of rough surfaces includes more boundary lubrication at earlier stage. In this case the coefficient of friction is high.

Table 3 Heat-treatment, metal structure and surface hardness of R specimens

Specimen number	Heat-treatment	Structure	Hardness Hv(500gr)		
			Cask specimen	Cylinder specimen	Mean
R1	Normalizing	Ferrite	264	266	265
		Pearlite	262	258	260
R2	After heating for 1 hr. at 850°C , cooling in furnace	Ferrite	231	224	228
		Pearlite	230	236	233
R3	After heating for 1 hr. at 850°C , quenching in water, followed by heating for 1 hr. at 530°C , then cooling in furnace	Sorbite	308	300	304
			299	296	298
R4	After heating for 1 hr. at 850°C , quenching in water, followed by heating for 1 hr. at 650°C , then cooling in water	Sorbite	315	307	311
R5	After heating for 5 hr. at 750°C , cooling to 700°C in furnace, and keeping for 8 hr. at 700°C , then cooling in furnace	Spheroidal pearlite	225	206	216
			205	202	204
R6	After heating for 1 hr. at 1000°C , quenching in water	Martensite	679	675	677
			618	696	657
R7	After heating for 1 hr. at 850°C , quenching in water, followed by heating for 1 hr. at 250°C , then cooling in furnace	Martensite	593	590	592
			598	592	595

Table 4 Heat-treatment, percentage of retained austenite and surface hardness of M specimens

Specimen number	Heat-treatment	Percentage of retained austenite(%)	Hardness Hv(500gr)	
			Cask specimen	Cylinder specimen
M1	Dew point: $-6.1 \sim -6.7^{\circ}\text{C}$ Carburizing temperature: 930°C After heating for 5 hr. in gas furnace, quenching in oil bath, followed by heating in 1 hr. at 140°C , then cooling in air	10.7	826	802
M2	Dew point: $-16.6 \sim -17^{\circ}\text{C}$ Carburizing temperature: 960°C After heating for 3 hr. in gas furnace, quenching in oil bath, followed by heating in 1 hr. at 140°C , then cooling in air	18.1	715	727
M3	Dew point: $-15 \sim -17^{\circ}\text{C}$ Carburizing temperature: 960°C After heating for 14 hr. in gas furnace, quenching in oil bath	49.2	600	605

Table 5 Test speed and specific sliding

Speed stage	Cask specimen		Cylindrical specimen		Sliding speed $V_2 - V_1$ (cm/s)	Specific sliding of cask specimen $\alpha = \frac{V_1 - V_2}{V_1}$
	Number of rotation n_1 (rpm)	circumferential speed V_1 (cm/s)	Number of rotation n_2 (rpm)	circumferential speed V_2 (cm/s)		
I	185	38.7	423	88.5	49.8	-1.29
II	400	83.7	918	191	108	-1.29

But with an increase in the time and the load, the surface roughness diminishes rapidly and then it becomes nearly constant. In the same manner as surface roughness, the coefficient of friction of contact surfaces converges to a constant value (nearly 0.06). The coefficient of friction in the specimen made of the case hardened steel is as low as about 0.04. The curves showing the relation between the coefficient of friction and the load can be classified into the ones shown in Fig.2(a) and Fig.2(b). Fig.2(a) shows an initial seizure which occurs on the small part of contact surface, but Fig.2(b) does not. Fig.3 shows the seizure load and the average Vickers hardness for many kinds of micro-structures in materials C and R.

The micro-structure of the test specimens can be classified into two groups of martensite and ferrite-pearlite. In the induction hardened specimen C18 whose micro-structure was martensite, the hardened depth was 3mm, and the seizure did not arise. In the specimens C15, R6, R7 whose micro-structure was also martensite, the seizure arose at high load. And in the specimens C16, C17 that contained not only martensite but also proeutectoid ferrite in the micro-structure, it was not easy for the seizure to arise. It seems that the proeutectoid ferrite was so little that the scoring limit was not influenced. In the specimens containing a little proeutectoid ferrite, the wear occurred in the proeutectoid ferrite and the worn surface was sunken and the hollow part played the role of an oil reservoir, therefore the lubrication took place rather in good condition. In the case of the martensite and retained austenite micro-structure (specimen numbers are from C8 to C14), if a little retained austenite was contained in micro-structure, — in the case of specimens C11 to C14 — and retained austenite contained was at least 8%, the initial seizure occurred in those specimens at low load from 300kg to 450kg and next a destructive seizure occurred at higher load. In those specimens containing a little retained austenite, as the hardness

Table 6 Contact area and shearing stress at the time when initial seizure occurs

Specimen number	Hv	W kg	ΔF kg	τ kg/mm ²	A mm ²
C7A	378	300	91.0	115	0.794
C11A	548	447	16.5	20.2	0.816
C11B	502	447	5.0	5.6	0.890
C12A	445	300	60.0	89.0	0.674
C12B	508	373	9.0	12.3	0.734
C13	473	447	6.0	6.4	0.945
C14A	478	300	12.3	19.6	0.628
C14B	464	300	110.0	170	0.647

was relatively high, the contact part did not easily develop plastic deformation, therefore it induced a relatively small contact area and a high contact pressure. In the hardened layer composed of fine structures, such as martensite and retained austenite, the thermal conductivity was relatively low and the flash surface temperature became high³. Therefore the seizure occurred at first in the part of retained austenite where the hardness was low. It is called the initial seizure and it is characterized by occurrence in the microstructure containing a relatively little retained austenite. The contact surface in which the initial seizure occurred was sheared and it resulted in a destructive seizure on the full contact surface under an increased load. On the other hand, the

C 1

C 2

C 6

C 9

C11

C13

C17

C18

50μ

Fig.1 Micrograph of metal structure

micro-structure containing much retained austenite in specimens C8 to C10 and containing 17.6 % maximum retained austenite has low hardness. Therefore the true contact area becomes larger than elastically calculated value due to the plastic deformation, and the true contact stress also becomes lower. In such surface layer, where the thermal conductivity is low and the area ratio of retained austenite is relatively large, the destructive seizure occurs on the full contact area at lower load stage, but a phenomenon such as initial seizure does not occur. The carburized and quenched steels (from M1 to M3) which con-

tain relatively much retained austenite not suffer the initial seizure either. In these cases, as shown in Fig.4, the specimen M1 which contain the least retained austenite does not suffer the destructive seizure at its load range, whereas the specimen M3 containing much retained austenite shows a lower hardness and a low destructive seizure load.

From these facts, it seems that the initial seizure is a local adhesion phenomenon. We now consider about its adhesion area. When the symbols are chosen as follows, Hv : Vickers hardness, W : load which causes the initial seizure kg, Y :

Fig. 2 Relation among load, surface roughness and coefficient of friction

Fig.3 Seizure load and mean hardness of each metal surface (C steel, R steel)

yield stress in tensile test kg/mm^2 , p_Y : yield strength at contact surface taking no account of work hardening kg/mm^2 . By the following equation⁵⁾ the yield strength p_Y may be calculated : $p_Y = (2.8 \sim 3)Y$. As the relation between the hardness H_v and the yield stress Y can be expressed by $H_v = 3Y$, it follows that $A = W/p_Y = W/H_v$. Where, A is the true contact area at the initial seizure. If the adhesion occurs

Fig.4 Relation between seizure load and percentage of retained austenite

Fig.5 Profile in a section which contains the cylindrical axis

- Curvature of cask specimen
- Curvature of cylindrical specimen
- Hertzian stress calculated from true curvature
- Hertzian stress calculated from initial curvature

Fig.6 Curvature and Hertzian stress changes with load

on this whole true contact area, the shearing force S to shear the adhesion face is expressed as follows : $S = A\tau = W\tau/H_v$, where τ is mean shearing stress of adhesion face. For example, for the specimen C7A, Hertzian stress required to cause the initial seizure is calculated as $\sigma_H = 250\text{kg/mm}^2$. (If a plastic deformation is taken into account, it is about 215kg/mm^2 .) And as the hardness of specimen C7A is 378Hv , the yield stress Y is estimated at about 126kg/mm^2 . Accordingly, the surface of apex of surface roughness has already yielded, but the whole apex and the neighborhood of contact surface do not yet yield. If the increment of frictional force ΔF at the initial seizure is equal to the shearing force S of adhesion face, the shearing stress τ can be calculated as in Table 6.

In specimens C7A, C12A and C14B where the initial seizure occurred under relatively low load, the shearing stress τ is fairly high, but in the others it is quite low. This result shows that the adhesion occurred on small area in all contact area and the size of adhesion area became clear.

In the group of ferrite and pearlite micro-structures the seizure load increases as follows : troostite < sorbite < ferrite and pearlite < spheroidal pearlite. But taking account of plastic deformation, the contact stresses at destructive seizure can be placed in different orders as described lately. Besides, the specimen C7A developed the initial seizure, but this did not show such a reproducibility as in the micro-structure containing a little retained austenite. Therefore it is difficult to presume that the source of initial seizure in C7A lies in micro-structure.

3.2 Change of surface shape

Fig.5 shows a sectional shape containing each axis on cylindrical and cask type specimens C18 under a load of 1925kg . The plastic deformation occurred not only in the apex of surface roughness but also in the bulk of specimen near the contact part. The height of surface roughness was reduced by the plastic deformation and wear, but unevenness still remained. As the radius of curvature is changed to increase the contact area, Hertzian stress and the surface roughness decrease. Therefore the oil film is easy to form between upper and lower specimens and the friction coefficient decreases at high load as shown in Fig.2.

Hertzian stress is modified by the relative radius of curvature calculated from the specimen's shape assumed as a parabola. Fig.6 shows an example of modified Hertzian stress. In Fig.6, the curvature of lower specimen is a negative value and the absolute values of curvatures of the upper and lower specimens become close to each other, so that Hertzian stress decreases. In Fig.6, the difference between Hertzian stresses calculated from the initial shape and taking the curvature change into account is insignificant in high hardness materials, but the difference is significant in low hardness materials. These changes in curvature radius involve the portion due to wear. It has been investigated from the measured curvature radius how the actual contact stress changes with each specimen hardness.

In Fig.7, Hertzian stress calculated from the initial shapes in the case of point contact is shown as the curve A, and this curve is expressed approximately as follows.

Fig.7 Relation among load, hardness and contact stress

Fig.8 Thermocouple for measuring of the oil film temperature

$$\sigma = 373 \left(\frac{W}{1000} \right)^{0.333} \quad (1)$$

The curve B shows Hertzian stress in the case of perfect yield, namely when the specimens contact fully on a line in the width direction. It seems that the contact stress in steels increases along the curve A in the range of relatively low loads. However, with an increase of the plastic deformation, the increment of stress decreases, and then the contact stress increases along the curve B with a still more increase of load.

Fig.7 shows the relation between contact stress and load at different specimen hardnesses. These relations are formularized by the following experimental equation.

Fig.9 Comparison of measured value of film temperature with calculated value of surface temperature

Fig.10 Change of hardness at surface and subsurface of specimen

$$\sigma = 373 \left(\frac{W}{1000} \right)^{0.333} - 11.3 \frac{\left(\frac{W}{1000} \right)^{0.5}}{\left(\frac{Hv}{1000} \right)^{1.72}} \quad (2)$$

where σ : contact stress kg/mm^2
 W : load kg
 Hv : Vickers hardness

3.3 Surface temperature

A thermo-couple of copper and constantan was attached on the rolling surface in order to measure the temperature of the oil film on surface. The diameter of the thermo-couple was 0.06mm and it was soldered as shown in Fig.8. The soldering of thermo-couple could be made easily by heating the constricted part of the glass tube in which the copper and constantan wires were interposed face to face. Fig.9 shows an example of these results.

The flash temperature of contact

Fig.11 Change of hardness in experiment

(a) Micrograph

(b) Diagram

Fig.12 Structure of seizure part

surface is calculated by the following formula⁶⁾:

$$\theta = \theta_{oil} + \frac{\sqrt{h}}{2} \frac{\mu \sigma (v_1 - v_2)}{\sqrt{\lambda} \gamma c} \frac{\sqrt{b}}{\sqrt{v_1 + v_2}} \quad (3)$$

where θ : flash temperature of contact surface

θ_{oil} : oil temperature

μ : coefficient of friction

σ : contact stress

b : short radius of Hertz contact ellipse

v_1, v_2 : circumferential speed

λ : thermal conductivity

c : specific heat

γ : specific weight

The measured values of μ , σ , b and the value of λ shown in the reference (3) were used here to calculate the flash temperature of the contact surface.

The calculated result given in Fig.9 shows that the temperature of oil film is lower than the flash temperature of the contact surface.

3.4 The change of hardness and micro-structure under rolling

According to the hardness change in the contact area measured after the experiment, the specimens C1 to C14 ($Hv \leq 500$) harden by scoring not only at the contact surface but also at a depth of 0.2mm below the surface, as shown in Fig.10. On the other hand, in the specimens C15 to 16 the

Fig.13 Photograph at part of seizure by electron microscope

Fig.14 Relation of hardness Hv with maximum contact stress σ_{max} when destructive seizure occurs

Fig.15 Relation of scoring limit with hardness
(θ oil=0)

hardness does not increase and in the specimens C17 and C18 it rather decreases. And the same results are obtained in the R-materials. Fig.11 shows the hardness change under rolling. In the micro-structure of ferrite-pearlite, spheroidal pearlite and sorbite, the hardness increases. On the other hand, the hardness of martensite micro-structure decreases at first, then it increases. This is because of the formation of retained austenite in the specimen heat-treated under the conditions of higher quenching temperature, fast cooling rate and no tempering.

The reason for more increase in the hardness after scoring seems to be as follows: In the micro-structure such as the ferrite-pearlite group and the retained austenite, the transformation from austenite to martensite occurs due to the heating under high pressure and the rapid cooling by the lubricating oil, as well as the work hardening caused by the compressive stress and the friction force at the surface. Fig.12(a) shows the micro-structure of specimen C2 after scoring. The hardness increases to the maximum increment of 387 Hv. Fig.13 shows a photograph of the parts C and D shown in Fig.12(b) under the electron microscope. The martensite is observed in Fig.13. It is generally known that the transformation temperature of the austenite decreases under the condition of the high compressive stress and such temperature arises by the frictional heating as in this experiment. According to Hilliard and Cahn⁷⁾, under the 340kg/mm² pressure the A₁ transformation temperature decreases to 645°C and the eutectoid point also changes to 0.28%C, so that the micro-structure is easy to change.

Besides, at the destructive scoring it is observed that the metal is transferred from the lower circumferential speed part to the higher part.

4. The relation between the scoring limit and hardness

It is obvious from this experimental result that the metal-structure in the gear materials has an important influence on the scoring limit. Assuming the hardness to represent the characteristic of metal-structure, except in the initial scoring, the maximum contact stress at the destructive scoring was compared with the hardness.

According to the result, the maximum contact stress increases with an increase of hardness as shown in Fig.14. Here, the maximum contact stress is the value calculated using the relation in Fig.7.

As shown in Fig.15, the increase of hardness has a tendency to increase the scoring limit, when the scoring limit is defined as the surface flash temperature calculated by using the formula (3) at the destructive scoring. It is therefore necessary to take the hardness and the metal-structure into account in the evaluation of the scoring limit in gear materials.

5. Conclusions

To study the influence of the metal-structure and hardness on the scoring limit, a scoring test was conducted on the carbon steel, the chromium steel and the carburized-quenched steel, which had been submitted to many kinds of heat treatment. As the result it is concluded as follows:

(1) The scoring limit is the highest in the martensite micro-structure. The thermal conductivity of the hardened structure is so small that the surface temperature due to the friction becomes high. If a little retained austenite is contained in the micro-structure, the initial seizure occurs. On the other hand, if much retained austenite is contained, the scoring limit decreases as the retained austenite increases.

(2) In the ferrite-pearlite group, the contact stress decreases as the hardness of the micro-structure decreases, because the plastic deformation increases as the hardness decreases. And the seizure load increases in appearance as follows.

troostite < sorbite < ferrite and pearlite
< spheroidal pearlite

But the scoring limit follows a different order.

(3) In the metal-structure of which the hardness is lower than 500Hv, the hardness increases under the repeated rolling contact. But in the martensite with high hardness, the hardness decreases a little.

(4) As the scoring limit is influenced by hardness, it is necessary to take the influence of the hardness or the metal-structure into account in the evaluation of the scoring limit.

References

- (1) Evans, L.S. and Turret, R., J. Inst. Petrol., Vol.38, No.344(1952-8), p.652.
- (2) Mansion, H.D., J. Inst. Petrol., Vol.38, No.344 (1952-8), p.633.
- (3) Terauchi, Y. et al., Bulletin of JSME, Vol.16, No.99 (1973-9), p.1443.
- (4) Terauchi, Y. et al., Bulletin of JSME, Vol.13, No.63 (1970-9), p.1123.
- (5) Bowden, F.P. and Tabor, D., The Friction and Lubrication of Solids, P.1, (1964), p.12, Oxford Univ. Press.
- (6) Coleman, W., Trans. ASME, Ser.F, Vol.89, No.2 (1967-4), p.114.
- (7) Nishiyama, Z., Martensite Transformation, Basic volume (1971), p.194, Maruzen. (in Japanese)