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ON THE SURFACE TEMPERATURE RISE AT THE FOUR-BALL TESTS *

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To examine the effect of mechanical properties, in particular, the compressive yield strength of a contacting ball on the surface temperature at the conjunctional area, the surface temperature is measured on a four-ball tester of Soda Type by means of the dynamic-thermocouples method in which the ball is electrically insulated from the tester. From the experimental results it would appear that when the Hertzian stress on the conjunctional area is smaller than the compressive yield strength of the contacting ball, variation of the surface temperature is remarkable due to the effect of the compressive yield strength, and the surface temperature is transiently minimum in the vicinity of the compressive yield strength of the ball.

1. Introduction

When the surface of a contacting body is considered to be smooth, the surface temperature generated instantaneously on the rubbing surface of such a contacting body has been theoretically derived from the continuous theory⁽¹⁾. As for the equation of the surface temperature of the ball at the four-ball tests, Fujita, et al.⁽²⁾ derived the equations of the flash temperature and the bulk temperature of the ball under an assumption that the heat is uniformly distributed on the conjunctional area.

In the present study, the surface temperature of a steel ball was measured by means of the dynamic-thermocouples method under the condition that the upper ball is electrically insulated from the four-ball test rigs, and the effect of the compressive yield strength of the steel ball on the surface temperature was examined. When the scoring resistance of the gears is judged by evaluating the critical surface temperature of the gear teeth, it will be necessary to clarify the effect of the compressive yield strength of the contacting body on the surface temperature.

2. Equation of surface temperature

The equation of the surface temperature of the ball at the four-ball tests could be derived under the following assumptions: The total heat generated frictionally flows across the rubbing surfaces of the balls without any loss. The manner of the heat being distributed on the conjunctional area may be decided by comparing the value of the maximum

Hertzian stress acting on the conjunctional area and that of the compressive yield strength of the ball as mentioned below.

When the maximum Hertzian stress generated on the conjunctional area is smaller than the compressive yield strength of the ball, it can be considered that the contact surface on the ball is elastically deformed, and the heat generated by the friction is paraboloidally distributed on the conjunctional area. Therefore, the equation of the surface temperature of the ball is given by the following equation (3).

$$\theta = \frac{4\mu PV \frac{8}{5} \sqrt{\frac{3}{2}} \sqrt{\frac{\kappa_1}{\pi V}}}{3\pi r JK_1 \left(\frac{K_2}{K_1} \frac{8}{5} \sqrt{\frac{3}{2}} \sqrt{\frac{\kappa_1}{\pi V}} + \frac{2}{3} \sqrt{r} \right)} \quad \text{---(1)}$$

On the contrary, when the maximum Hertzian stress exceeds the compressive yield strength of the ball, it can be considered that the contact surface on the ball is plastically deformed, and the heat is uniformly distributed on the conjunctional area. The equation of the surface temperature of the ball is given by:

$$\theta = \frac{2\mu PV \sqrt{\frac{2\kappa_1}{\pi V}}}{\pi r JK_1 \left(\frac{K_2}{K_1} 2 \sqrt{\frac{2\kappa_1}{\pi V}} + \sqrt{r} \right)} \quad \text{-----(2)}$$

where

- J : Mechanical equivalent of heat
kgf-cm/cal
- K : Thermal conductivity of the ball
cal/(cm s °C)
- P : Load
kgf
- V : Sliding velocity
cm/s
- r : Radius of conjunctional area on the ball
cm
- μ : Coefficient of friction
- κ : Thermal diffusivity of the ball
cm²/s

Subscripts 1 and 2 stand for the upper ball (the rotating ball) and the lower ball (the fixed ball), respectively.

3. Measurement of surface temperature of the ball at the " Soda " four-ball test rigs

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Table 1 Chemical compositions of the steel balls A and B

Composition %	C	Si	P	S	Cr	Mn
Steel ball A	1.00	0.33	0.019	0.019	1.51	0.41
Steel ball B	0.98	0.32	0.019	0.007	1.40	0.42

Table 2 Micro-Vickers hardness and compressive yield strength of steel ball B

Normalizing temperature °C	800	600	500	350	250	170
Micro-Vickers hardness Hv	230~240	320~330	420~430	590~600	680~710	790~810
σ_y kgf/mm ² *	—	140	170	190	220	240

* Compressive yield strength

3.1 Test balls and test rigs

The test balls used in this experiment are steel balls A and B, and these balls contain different amounts of chromium. The diameter of the ball is 19.05 mm (3/4 in) and the average sphericalness of its ball is 0.18 μ m. Their chemical compositions are given in Table 1, and the content of chromium composition in steel ball B is only a little compared with that in steel ball A. Steel ball A is normalized at 170 °C after quenched from 900 °C. On the other hand, steel ball B is normalized at 800, 600, 500, 350, 250 and 170 °C after quenched from 900 °C. The Micro-Vickers hardness (weight: 200 gf) and the compressive yield strength of steel ball B are given in Table 2.

The compressive yield strength of steel ball B is measured by the following method: After the ball B coated with thinner soot is set on the four-ball tester, the balls are pressed against each other with a load P under the stationary condition. The load is removed, and the diameter d_0 of the contact spots produced on the ball B (three fixed balls) is measured. The apparent average contact pressure p_m acting on the contact spots is evaluated from the equation $p_m = 4P/(\pi d_0^2)$. In this section, the compressive yield strength of the ball may be defined as the apparent average contact pressure at the position where the gradient of the curve of p_m against P varies. For example, the gradient of the curve of p_m against P in the case of the ball normalized at 600 °C varies in the vicinity of $p_m = 140$ kgf/mm² as shown in Fig. 1, and the value of p_m about coincides with the compressive yield strength σ_y of the ball.

Fig. 1 Relation between the load and the apparent average contact pressure of the ball normalized at 600 °C

Fig. 2 Schematic diagram of the four-ball tester

As shown in Fig. 2, steel ball A is used for the upper ball, and steel ball B is used for the lower ball. The upper ball and the carbon ring are electrically insulated from the four-ball test rigs, respectively. Therefore, the electro-motive force generated in the dynamic-thermocouple circuit formed by the upper and the lower balls can be measured by a potentiometer placed in the circuit. The lead wire connecting the ball A and the carbon ring is made of the same material as ball A. The electro-motive force generated in the thermocouple circuit is approximately 2 μ V at 1 °C. The frictional force between the upper and the lower balls can be estimated by measuring the torsional angle of the shaft supporting the bowl in which the three lower balls are clamped immovably together.

3.2 Lubricant

The balls are lubricated with a 140 turbine oil, and the oil temperature is controlled at 20 ± 2 °C by the thermostat while the tests are going on. The upper ball is immersed about 1/3 diameter deep into the oil bath. The load is increased in steps at a rate of approximately 2.0 kgf in 12 sec. The viscosity of the oil is 90 cSt at 25 °C, 18 cSt at 60 °C and 8 cSt at 90 °C.

4. Test results and observations

4.1 Variation of coefficient of friction

Figure 3 shows the variation of the coefficient of friction against the load when the sliding velocity between the balls is 12.6 cm/s. For the case of $P < 2.5$ kgf, the value of the coefficient of friction cannot be strictly evaluated because the measured value of the frictional force is remarkably small. In this figure, the variation of the coefficient of friction against the load is depicted by a broken line until the load is 2.5 kgf.

In the case of the ball normalized at 800 °C after quenched from 900 °C, the value of the coefficient of friction tends to increase with an increasing load up to 20

Fig.3 Variation of the coefficient of friction with the load when the sliding velocity between the balls is 12.6 cm/s

kgf, and that of the coefficient of friction is approximately 0.07 and remains constant when the load exceeds 20 kgf. On the other hand, in the case of the ball normalized at 600, 350 and 170 °C, the value of the coefficient of friction remarkably increases until the load is about 5 kgf. When the load lies between 5 kgf and 20 kgf, the value of the coefficient of friction somewhat varies. However, when the load exceeds 20 kgf, the value of the coefficient of friction is about 0.08 and remains constant, independently of the load.

4.2 Diameter of wear scar

Fig.4 Variation of the diameter of the wear scar of the ball with the load

Figure 4 shows the variation of the diameter of the wear scar of the lower ball against the load when the sliding velocity between the balls is 12.6 cm/s. The diameter of the wear scar indicates the average value of the diameter of the wear scar produced on the three fixed balls (the lower ball). The diameter of the wear scar is measured by the following method: The load is increased in steps at a rate of approximately 2.0 kgf in 12 sec from the unloaded condition, and the diameter of the wear scar is measured at every load. In this case, the ball is replaced by a new ball at every test. The measurement of the frictional force is omitted in this test. From this figure it is clear that the diameter of the wear scar increases with an increasing normalizing temperature of the ball. The diameter of the wear scar of the ball normalized at 800 °C is larger than that of the ball normalized at a different temperature, and the diameter of the wear scar increases in proportion to the load.

4.3 Variation of surface temperature

Figure 5 shows the variation of the measured value of the surface temperature of the ball normalized at 170 °C against the load when the sliding velocity between the balls is 12.6 cm/s. For the case of $P < 2.5$ kgf, the surface temperature of the ball can not be exactly estimated since the measured value of the electro-motive force is very small and it also varies with a short frequency. Therefore, the variation of the surface temperature against the load is depicted by broken line until the load is 2.5 kgf (see Figs.5 through 8). As shown in Fig.5, the surface temperature remarkably increases up to about 80 °C just after the running tests, and subsequently the surface temperature remarkably decreases with an increasing load. The minimum value of the surface temperature occurs in the vicinity of the load of 10.8 kgf (the maximum Hertzian stress $p_0 = 230$

Fig.5 Measured value of the surface temperature of the ball normalized at 170 °C when the sliding velocity between the balls is 12.6 cm/s

kgf/mm²). After that, the surface temperature remarkably increases with an increasing load. However, when the load exceeds 23 kgf, the increase in the surface temperature tends to be comparatively small with an increasing load. The experimental results in which the minimum value of the surface temperature occurs in the vicinity of the maximum Hertzian stress $p_0 = 230$ kgf/mm² can be similarly obtained from the three tests. The above-cited fact can be also observed with the experimental results obtained by Soda⁽⁴⁾. From the compression tests of the ball set on the four-ball tester it can be seen that the compressive yield strength of the ball normalized at 170 °C is approximately 240 kgf/mm², and the minimum value of the surface temperature occurs at the load at which the maximum Hertzian stress acting on the conjunctional area is approximately equal to the compressive yield strength of the ball.

Figure 6 shows the variation of the measured value of the surface temperature of the ball normalized at 170 °C against the load when the sliding velocity between the balls is 43.2 cm/s. The variation of the surface temperature against the load at a comparatively high speed is similar to that of the surface temperature at a low speed as shown in Fig. 5, and the minimum value of the surface temperature occurs in the vicinity of the load 10.8 kgf. After that, the surface temperature remarkably increases with an increasing load. When the load exceeds 25 kgf, the increase in the surface temperature is comparatively small with an increasing load. From this figure it is clear that the surface temperature increases with an increasing sliding velocity. However, the minimum value of the surface temperature occurs at the load at which the maximum Hertzian stress is approximately equal to the compressive yield strength of the ball, and the magnitude of the load is independent of the sliding velocity.

Figure 7 shows the variation of the surface temperature of the ball normalized at 600 °C against the load when the sliding

Fig. 6 Measured value of the surface temperature of the ball normalized at 170 °C when the sliding velocity between the balls is 43.2 cm/s

Fig. 7 Measured value of the surface temperature of the ball normalized at 600 °C when the sliding velocity between the balls is 12.6 cm/s

velocity between the balls is 12.6 cm/s. The variation of the surface temperature of the ball against the load is similar to that of the surface temperature of the ball normalized at 170 °C. The surface temperature remarkably increases up to approximately 65 °C just after the running tests, and subsequently the surface temperature remarkably decreases with an increasing load. The minimum value of the surface temperature occurs in the vicinity of the load 3.6 kgf (the maximum Hertzian stress $p_0 = 161$ kgf/mm²). This Hertzian stress is approximately equal to the compressive yield strength $\sigma_y = 140$ kgf/mm² of the ball normalized at 600 °C. After that, the surface temperature remarkably increases with an increasing load. When the load exceeds 10 kgf, the increase in the surface temperature is relatively small against an increasing load. The variation of the surface temperature with the load as mentioned above can be similarly obtained from the three tests.

Figure 8 shows a typical variation of the measured value of the surface temperature of the ball normalized at 170, 350, 600 and 800 °C with the load when the sliding velocity between the balls is 12.6 cm/s. The surface temperatures of the ball normalized at 170, 350 and 600 °C vary with same tendency, excluding the ball normalized at 800 °C. For the case of the ball normalized at 170, 350 and 600 °C, the surface temperature remarkably increases just after the running tests. After that, the surface temperature remarkably decreases with an increasing load, and subsequently the surface temperature remarkably increases with an increasing load. However, the load at which the minimum value of the surface temperature occurs differs due to the variation of the normalizing temperature of the ball, and it decreases with an increasing normalizing temperature of the ball. For instance, the minimum value of the surface temperature of the ball normalized at 170,

350 and 600 °C occurs at the loads 10.8, 6.5 and 3.6 kgf, respectively. And the maximum Hertzian stresses corresponding to these loads are 230, 200 and 161 kgf/mm², respectively. Therefore, it seems that these stresses approximately coincide with the compressive yield strength of the ball as shown in Table 2. On the other hand, the surface temperature of the ball normalized at 800 °C linearly increases with an increasing load. The compressive yield strength of the ball can not be detected by the compression tests carried out using the four-ball tester because the load at which the contact surface on the ball yields is remarkably small. From this figure it is clear that the load at which the minimum value of the surface temperature occurs decreases with an increasing normalizing temperature of the ball. For the case of the ball normalized at 800 °C, the minimum value of the surface temperature can not be detected, and the surface temperature increases with an increasing load.

Figure 9 shows the variation of the surface temperature with the load which is calculated by substituting the measured values of the coefficient of friction and the diameter of the wear scar on the four-ball tests into Eqs. (1) and (2) of the surface temperature. For the case of $P < 2.5$ kgf, since the coefficient of friction can not be exactly estimated as mentioned before, the variation of the surface temperature with the load is depicted by the broken line until the load is 2.5 kgf. The surface temperature is evaluated under the following conditions: The thermal conductivities of the material of the ball normalized at 800, 600, 350 and 170 °C are estimated at 0.09⁽⁵⁾, 0.085, 0.08 and 0.066 cal/(cm s °C), respectively, because the thermal conductivity decreases with a decreasing normalizing temperature⁽⁶⁾. However, the specific heat c and the specific gra-

vity γ of the material of the ball are $c = 0.108$ kcal/(kgf °C)⁽⁵⁾ and $\gamma = 7.9 \times 10^{-3}$ kgf/cm³, respectively, under an assumption that these values are independent of the variation of the normalizing temperature.

When the maximum Hertzian stress acting on the conjunctural area does not exceed the compressive yield strength of the lower ball, the surface temperature of the ball can be evaluated from Eq. (1) under an assumption that the heat generated by friction is paraboloidally distributed on the conjunctural area since the contact surface can be considered to be elastically deformed. On the contrary, when the maximum Hertzian stress exceeds the compressive yield strength of the ball, the surface temperature can be evaluated from Eq. (2) under an assumption that the heat is uniformly distributed on the conjunctural area since the contact surface can be considered to be plastically deformed.

When the total amount of the heat of a paraboloidally distributed heat source is assumed to be equal to that of the heat of a cylindrically distributed heat source, the maximum heat quantity (the heat quantity generated per unit area and unit time) of the former is 2 times larger than that of the latter.

For the case of the ball normalized at 170 °C, the surface temperature is evaluated from Eq. (1) since the contact surface can be considered to be elastically deformed until the load is 8.5 kgf. On the other hand, the surface temperature is evaluated from Eq. (2)

Fig. 8 Measured value of the surface temperature of the ball normalized at 170, 350, 600 and 800 °C when the sliding velocity between the balls is 12.6 cm/s

Fig. 9 Calculated value of the surface temperature of the ball normalized at 170, 350, 600 and 800 °C when the sliding velocity between the balls is 12.6 cm/s

since the contact surface can be considered to be plastically deformed when the load exceeds 10.8 kgf.

From the calculated results of the surface temperature of the ball normalized at 800 °C, it can be seen that the surface temperature remarkably increases up to approximately 54 °C just after running tests because the coefficient of friction remarkably increases. After that, the surface temperature decreases with an increasing load because the coefficient of friction decreases and the diameter of the wear scar of the ball increases with an increasing load. The minimum value of the surface temperature occurs at the load 10.8 kgf, and then the surface temperature remarkably increases with an increasing load. And the increase in the surface temperature is comparatively small when the load exceeds 18 kgf. The calculated value of the surface temperature is a little lower than the measured value of the surface temperature. However, the variation of the calculated value of the surface temperature with the load well coincides with that of its measured value, and the minimum value of the surface temperature is observed at the load at which the maximum Hertzian stress acting on the conjunctural area coincides with the compressive yield strength of the ball.

Similarly, the minimum value of the surface temperature of the ball normalized at 350 °C occurs at the load 8.5 kgf, and the load approximately coincides with the load at which the minimum value of the surface temperature is measured. On the other hand, the surface temperature of the ball normalized at 800 °C is evaluated from Eq.(2) since the contact surface of the ball can be considered to be plastically deformed. The surface temperature of the ball increases with an increasing load, and the variation of the calculated value of the surface temperature with the load is similar to that of the measured value of the surface temperature. Therefore, when the load per unit ball does not exceed 17 kgf (the load is equal to the gauge pressure of about 1 kgf/cm² at the pressure gauge set on the four-ball tester), the mechanical strength, in particular, the compressive yield strength of the ball plays a major role in the surface temperature of the ball and thereby the surface temperature transiently decreases at the load at which the maximum Hertzian stress acting on the conjunctural area approximately coincides with the compressive yield strength of the ball.

When the maximum Hertzian stress does not exceed the compressive yield strength of the ball, the heat generated by friction can be assumed to be paraboloidally distributed on the conjunctural area. On the contrary, when the maximum Hertzian stress exceeds the compressive yield strength of the ball, the heat can be assumed to be uniformly distributed on the conjunctural area.

5. Conclusions

The calculating and the experimental results of the surface temperature of balls with different compressive yield strengths at the four-ball tests are summarized as follows :

- (1) When the maximum Hertzian stress acting on the conjunctural area does not exceed the compressive yield strength of the ball, the variation of the surface temperature is remarkable due to the effect of the compressive yield strength of the ball and thereby the surface temperature transiently decreases at the load at which the maximum Hertzian stress approximately coincides with the compressive yield strength of the ball. After the contact surface is plastically deformed, the increase in the surface temperature is small as compared with an increasing load.
- (2) When the gauge pressure of the pressure gauge set on the " Soda " four-ball tester exceeds 1 kgf/cm², the surface temperature of the ball can be evaluated from the equation of the surface temperature derived under the assumption that the heat generated by friction is uniformly distributed on the conjunctural area of the ball.

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