The Mechanism of Seizure in Two-Roller Tests*

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From observations of the metallic structure at the seized portion in two-roller tests and the calculation of the stress resulting from the combination of the Hertzian stress field, the frictional force field and the thermal stress field on the contacting rollers, it was found that the seized portion on the rollers adhered to the surface of the lower roller rotating at high speeds and that its hardness was considerably high; and that the portion could be easily separated from the surface of the lower roller. The mechanism of adhesion can be considered as follows: as the shearing stress (Hertzian stress + frictional force + thermal stress) acting on the upper roller is larger than that on the lower roller, the portion of the upper roller, at which the distribution of the hardness below the surface of the roller is minimum, is sheared due to the shearing stress, and adheres to the surface of the lower roller.

Key Words: Friction, Seizure, Lubrication, Shearing Force, Thermal Stress

1. Introduction

There are a great number of reports in which the scoring resistance of gears and the mechanism of scoring were investigated using a two-roller machine. One of the authors has investigated the effects of the structure and the hardness of the material on the seizure resistance of the rollers with a two-roller machine⁽¹⁾. From the test against seizure of the rollers, it was found that the weight of the roller rotating at high speeds increased at the incipient stage of seizure⁽²⁾. The above-cited test results were obtained with the two-roller tests which were performed by Hirano, et al. under dry friction⁽³⁾. However, the problems of the adhesion, i.e. why the seized portion adheres to the contacting surface of the roller rotating at high speeds, still remain to be investigated.

In this report, from observations of the metallic structure at the seized portion of the carburizing hardened rollers in two-roller tests and the calculation of the stress on and below the surface of the roller, the mechanism of the adhesion of the wear particles at the incipient stage of seizure was examined.

2. Experimental Method

2.1 Test machine

The two-roller tests were carried out using an Amsler's machine in which the load unit was improved so that the load could be controlled by oil pressure. The oil pressure acted on the machine frame with an upper roller. With respect to the measurement of frictional force, the displacement of the pendulum mounted on the shaft of the test machine was detected by a differential transformer. The risk against seizure of the rollers was estimated from an unsteady variation in frictional force.

2.2 Lubricating oil

The rollers were lubricated with # 140 turbine oil (with kinematic viscosities of $28 \times 10^{-6} \text{ m}^2/\text{s}$ at 323 K and $8 \times 10^{-6} \text{ m}^2/\text{s}$ at 363 K) which was a straight

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mineral oil without additives. The roller tests were carried out under forced lubrication, and the oil was sprayed onto the contacting surfaces of the rollers at a rate of 0.3 L/min. The oil temperature was controlled to 293 ± 4 K by a thermostat.

2.3 Test specimens and experimental method

The rollers (barrel and cylinder types rollers) used in two-roller tests were made of SCM 415 H material. The rollers were oil-quenched at 1073 K after being carburized at 1173 K, then they were ground. Their surfaces had a Vickers microhardness of approximately 720 HV. As shown in Table 1, the radius and the width of the upper and lower rollers (cylinder-type roller) were 40 mm and 10 mm, respectively. To grind the barrel-type roller, a grinder in which the grinding wheel rounds the roller in a concave arc was used. The crowning radius in the axial direction of the barrel-type roller was 20 mm. The surface roughness in the circumferential direction of the barrel- and cylinder-type rollers was $3 \mu\text{m } R_{\text{max}}$ and $2 \mu\text{m } R_{\text{max}}$, respectively. The roughness in the axial direction of the barrel- and cylinder-type rollers was approximately $6 \mu\text{m } R_{\text{max}}$ and $3 \mu\text{m } R_{\text{max}}$, respectively.

Tests were carried out for the case of the roller pair combined with two types of rollers: the roller pair in Test 1 consists of a barrel-type roller (upper roller) and a cylinder-type roller (lower roller). On the other hand, the roller pair in Test 2 consists of a cylinder-type roller (both upper and lower rollers).

The peripheral velocities and the specific slidings of the upper and lower rollers are shown in Table 1. The load was increased stepwise at the peripheral velocity shown in Table 1, and the test machine was run continuously until seizure occurred. The tests were carried out under a load of 974 N, and the load was increased by about 243 N increments during the initial 10 s, and was kept constant for 50 s.

3. Results and Discussion

3.1 Seizure resistance

Figure 1 shows the calculated values of the flash temperature rise θ_f and the maximum Hertzian stress p_0 at the incipient stage of seizure of the roller pairs in Tests 1 and 2. The flash temperature rise was calculated by Blok's equation⁽⁴⁾, and the value of the coefficient of friction was given from the measured value just before seizure occurred. The Hertzian stress and the flash temperature rise at the incipient stage of seizure of the roller pair in Test 1, where the rollers were assumed to have point contact, are higher than those in Test 2, where the rollers were assumed to have line contact, and the flash temperature rise of the roller pair in Test 1 was approximately 250 K higher

than that in Test 2. For the case of Test 1, the temperature at the incipient stage of seizure was significantly high.

When a minimum oil film thickness was calculated by Cheng's equation in an elliptical contact⁽⁵⁾ and by Dowson's equation in a line contact⁽⁶⁾, the film thicknesses of the roller pairs in Tests 1 and 2 were $0.21 \mu\text{m}$ and $0.19 \mu\text{m}$, respectively. As the value of λ , defined by Wellauer⁽⁷⁾ (the ratio of the film thickness to combined surface texture), was approximately 0.6, the tests were run under almost metallic contact.

3.2 Observations of seized portion

Figures 2(a) and (b) show the profile of the wear track in the axial direction of the upper and lower rollers after seizure occurred for the case of the roller pairs in Tests 1 and 2. For both roller pairs, the wear track on the upper roller (specific sliding is negative) was plowed out. On the contrary, the wear track on the lower roller (specific sliding is positive) was protruding, and a part of the wear track on the upper roller was transferred to the contacting surface of the lower roller. The above-cited test results were also obtained with the tests previously carried out by

Table 1 Specifications of test rollers and test conditions

	Peripheral velocity V , m/s	Specific sliding ϵ	Radius R , mm	Width b , mm
Upper roller	0.72	-2.069	20	10
Lower roller	2.21	0.674	20	10

Fig. 1 Flash temperature rise and maximum Hertzian stress at the incipient stage of seizure

the authors⁽²⁾ for the case of the roller pairs with a considerably low hardness, which were made of SUJ1 material and were annealed at 1 073 K.

As an example, Fig. 3(a) shows a microphotograph of the wear track of the upper roller in Test 2 after seizure occurred. An undulation like a scale was observed in the rotatory direction of the roller, and the surface layer of the roller was sheared in the acting direction of the frictional force. Figure 3(b) shows a microphotograph of the sectional plane cut in the axial direction of the roller at the bottom of the undulated portion in Fig. 3(a) and the distribution of Vickers microhardness measured along a line A-A. The sectional plane of the roller was etched with 5% nital liquid. From this photograph, it can be seen that

the structure at the bottom of the undulated portion of the roller consisted of two layers in which the degree of etching was progressive and/or unprogressive, and the boundary between these layers was clear. However, the upper layer could not be separated from the wear track due to the impact of a hammer. Therefore, the layer was regarded as the metallic structure affected by the actions of the frictional force and the frictional heat. The structure in the vicinity of the surface of the race and balls at the rolling bearing unit which was run for a long time was varied, and the structure is termed a white etching constitution. A layer with a considerably high hardness was observed with our roller tests. The hardness within the layer in which the degree of etching was progressive was

Fig. 2 Profile of wear track in the axial direction of test rollers after seizure occurred

Fig. 3 Microphotograph of seized portion of upper roller in Test 2

about 900HV, and the hardness in the vicinity of the boundary of the layer, in which the degree of etching was progressive, significantly decreased. However, the hardness within the etched layer, which was affected by the actions of the frictional force and the thermal stress, was a little higher than that before tests, and considerably lower than that within the unetched layer. A significant increase in the hardness within the surface layer of the roller after seizure occurred is considered to be caused by the work-hardening due to the actions of the compressive stress, the frictional force and the thermal stress, etc., as mentioned below, and by the variation in the metallic structure due to the cooling action of lubricating oil.

Similarly, Fig. 4(a) shows a microphotograph of the wear track of the lower roller in Test 2 after seizure occurred. Comparing it with the seized portion of the upper roller, the degree of surface failure by seizure was remarkable, and the adhered portions were overlapped in a V in the acting direction of the frictional force. Figure 4(b) shows a microphotograph of the sectional plane cut in the circumferential direction of the roller shown in Fig. 4(a) and the distribution of Vickers microhardness measured along

a line *B-B*. The layer transferred from the upper roller at the incipient stage of seizure with a comparatively high hardness, in which the degree of etching was unprogressive, was observed. In the adhered portion, the lamellar structure which is caused by a plastic flow was observed in the acting direction of the frictional force. The hardness at the center of the adhered portion was considerably high. However, the hardness in the vicinity of the boundary between the adhered portion and the contacting surface of the roller was low. Figure 4(c) shows a microphotograph of the sectional plane cut along a line *B-B* (sectional plane cut in the axial direction of the roller) in Fig. 4(b). The contacting surface of the roller was considerably smooth, and was unaffected by seizure. Further, a few vacancies were observed between the contacting surface and the adhered portion, and a few parts of the adhered portion adhered to the contacting surface. The portion could be easily separated from the contacting surface due to the impact of a hammer.

The phenomenon that a part of the wear track on the upper roller (specific sliding is negative) is transferred to the contacting surface of the lower roller (specific sliding is positive) at the incipient stage of seizure can be considered to be caused by the fact that the action of the stress resulting from the combination

Fig. 4 Microphotograph of seized portion of lower roller in Test 2

of the Hertzian stress field, the frictional force field and the thermal stress field on the contacting surface of the upper roller is different from that of the lower roller.

3.3 Mechanisms of metallic transfer at seized portion

The authors previously clarified that the thermal stress could be analytically evaluated under an assumption of a one-dimensional heat flow in which the heat flux enters in the normal direction of the conjunctural area when a parabolically distributed heat source moves with a comparatively high velocity on the contacting surface⁽⁹⁾. Figure 5 shows the coordinates of the roller in two-roller tests. In this figure, the subscripts 1 and 2 relate to the upper and lower rollers, respectively. The maximum value of the heat intensity q_0 generated per unit time is given by the following equation when the distribution of heat intensities is parabolic,

$$\mu P |V_1 - V_2| = 4q_0 l / 3 \quad (1)$$

where P is the normal load per unit width, V is the peripheral velocity, l is a half of the Hertzian contact width, μ is the coefficient of friction. When the rates of the heat quantity flowing from each point of the conjunctural area into the upper and lower rollers are expressed by ψ and $1-\psi$, respectively, the surface temperature at the point of the conjunctural area of the lower roller is equivalent to that of the upper roller. Therefore, the value of ψ becomes as follows:

$$\psi = \sqrt{V_1} / (\sqrt{V_1} + \sqrt{V_2}) \quad (2)$$

Multiplying the calculated value of the thermal stress by ψ and $1-\psi$, the stress σ_{xx} acting in the moving direction of the heat source, the stress σ_{zz}

acting in the normal direction of the conjunctural area and the shearing stress τ_{xz} acting on the upper and lower rollers can be obtained.

On the other hand, when the frictional force f expressed by $f = \mu p_0$ acts on the contacting surface of the roller, the stresses σ_{xx} , σ_{zz} and τ_{xz} occurring on and below the surface of the roller can be calculated by Smith's equation⁽⁹⁾.

The values of the thermal and mechanical properties of the roller are shown in Table 2⁽¹⁰⁾.

As an example, the distributions of the isothermal line of the stresses σ_{xx} , σ_{zz} and τ_{xz} resulting from the combination of the Hertzian stress field, the frictional force field and the thermal stress field of the upper and lower rollers at the incipient stage of seizure for the case of Test 2 are shown in Figs. 6(a)~(c) and Figs. 7(a)~(c), respectively. The value of the coefficient of friction is given from the measured value just before seizure occurred. In Figs. 6 and 7, the ordinate and abscissa indicate the position of the evaluated stress in terms of the dimensionless parameters Z/L and X/L , respectively, where $X = Vx/(2\kappa)$, $Z = Vz/(2\kappa)$, $L = Vl/(2\kappa)$ and κ stands for the thermal diffusivity of the roller.

For the case of the stress distribution of the upper roller shown in Fig. 6, the component of the thermal stress indicates the calculated value when the center of the heat source moves from the negative portion in the x -axis to the origin 0. The maximum value of the temperature rise due to a one-dimensional heat flow when the distribution of heat intensity is parabolic occurs at $X/L = -0.5$ behind the origin, and the value of the thermal stress due to the action of the frictional heat is largest when the center of the heat source reaches the origin. On the other hand, the frictional force occurring within the region of the contact width $(-1.0 \leq X/L \leq 1.0)$ acts from the positive portion of

Fig. 5 Coordinates of roller in two-roller test

Table 2 Thermal and mechanical properties of rollers

Coefficient of thermal expansion α , $1/^\circ\text{C}$	12.7×10^{-6}
Thermal conductivity K , $\text{W}/(\text{mK})$	24
Thermal diffusivity κ , m^2/s	6.667×10^{-6}
Specific heat c , $\text{kJ}/(\text{kgK})$	0.461
Density ρ , kg/m^3	7870
Young's modulus E , GPa	206
Poisson's ratio ν	0.3
Shear modulus G , GPa	80.8

Fig. 6 Distribution of resultant stress acting on upper roller at the incipient stage of seizure

Fig. 7 Distribution of resultant stress acting on lower roller at the incipient stage of seizure

the x -axis to the negative portion. The effect of the thermal stress on the stresses σ_{xx} and τ_{xz} is larger than that of the frictional force. On the contrary, the effect of the thermal stress on the stress σ_{zz} is remarkably small. The maximum value of the stress σ_{xx} occurs on the surface and at a little distance behind the center of the heat source. The stress σ_{xx} at this position is compressive stress. The maximum value of the stress σ_{zz} occurs on the contacting surface, and the profile of the distribution of the stress σ_{zz} is approximately symmetrical against the origin. The maximum value of the shearing stress τ_{xz} occurs below the surface and at two positions before and behind the origin. The profile of the distribution of the stress τ_{xz} is complicated.

For the case of the lower roller, as shown in Fig. 7, since the moving direction of the heat source coincides with the sliding direction (the acting direction of the frictional force), the action of the stress which is caused by the frictional force is superimposed upon that by the thermal stress. Therefore, the maximum value of the stress σ_{xx} acting on the lower roller

is larger than that on the upper roller. With respect to the stress σ_{zz} , the profile of the distribution of the stress acting on the lower roller is approximately similar to that on the upper roller, and the maximum value of the stress occurs on the surface. On the other hand, with respect to the shearing stress τ_{xz} playing a significant role in the fracture of the contacting surface, the maximum value of the stress occurs below the surface. Further, the maximum value of the stress acting on the upper roller is larger than that on the lower roller, and the amplitude of the former is larger than that of the latter.

Figure 8 shows the distribution of the maximum value of the positive and negative components of the shearing stress acting on the upper and lower rollers for the case of Test 2 and the distribution of the hardness of the roller before the test. The shearing stress acting in the vicinity of the surface of the upper roller is considerably larger than that of the lower roller. Therefore, the surface layer of the roller is work-hardened due to the action of repeated stresses resulting from the combination of the frictional force

Fig. 8 Distributions of shearing stress on and below surface at the incipient stage of seizure and hardness of roller before test

field and the thermal stress field, and the mechanical properties of the contacting surface increase. The layer cannot be fractured due to the action of the shearing force acting on the surface of the roller. However, since the value of the shearing force occurring at the position where Vickers microhardness of the roller is minimum (arrow mark) for the case of the upper roller is larger than that of the lower roller, it can be considered that a part of the wear track on the upper roller is sheared at the position indicated by the arrow mark, and adheres to the surface of the lower roller. As shown in Figs. 2 and 3, the depth of the hollow occurring on the contacting surface of the upper roller after seizure occurred is approximately $40\text{ }\mu\text{m}$, and agrees well with the depth where the fracture of the roller occurs due to the action of the shearing stress.

4. Conclusions

The tests against seizure of the roller with high hardness were carried out using the two-roller machine. From observations of the metallic structure

at the seized portion with a microscope, the measurement of the hardness of this portion and the calculation of the stress resulting from the combination of the contact stress field, the frictional force field and the thermal stress field, the following results were obtained.

A part of the wear track on the upper roller (specific sliding is negative) is transferred to the contacting surface of the lower roller (specific sliding is positive) at the incipient stage of seizure, and the hardness of the seized portion is considerably high. It can be considered that they are caused by work-hardening due to the actions of the compressive stress, the frictional force and the thermal stress and by the variation in the metallic structure due to the cooling action of the lubricating oil. With respect to the mechanism in which the seized portion is transferred to the contacting surface, as the shearing stress (Hertzian contact stress + frictional force + thermal stress) acting on the upper roller is larger than that on the lower roller, a part of the wear track on the upper roller is fractured due to the action of the shearing stress occurring at the position where the hardness of the roller is minimum, and adheres to the contacting surface of the lower roller.

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