539. 431. 3:621. 822

Fatigue Strength of White Metal Lining on Steel Plate*

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Plane bending fatigue tests are carried out on a white metal lining on a steel plate to clarify the fatigue failure of plain bearings under fluctuating loads. The fatigue strength of the metal is discussed in terms of the crack propagation rate under various test conditions. The fatigue strength is affected by lining thickness, operating temperature, and the viscosity and activity of the lubricating oil.

From the analysis of each factor, the following are known quantitatively. The effect of lining thickness is due to the binding of strain at the tip of fatigue cracks. The effect of the operating temperature is due to the variation of physico-chemical properties of lubricants as well as the variation of mechanical properties of the metal. The viscosity of lubricant varies the oil pressure in the wedge of the crack where the oil penetrates according to its viscosity. The fatigue strength of the metal is also decreased by the chemical adsorption of lubricants at the tip of fatigue cracks.

1. Introduction

The failure of a plain bearing under fluctuating loads is frequently due to fatigue, where fine fatigue cracks grow gradually in the lining metal, resulting in separation at interface with the backing metal. For this type of failure, the load capacities or the running lives of bearings have been estimated by endurance tests using a bearing testing machine. It is inadequate, however, to find out the fatigue strength and the mechanism of bearing failure from these estimations because the load capacities determined by the pressure on projected area vary with constructions and running conditions of the bearing. As for the fatigue strength of lining metal, since bearings in service run with lubricating oil at high temperature, it is not enough to judge the fatigue strengths by testing a solid metal in air.

In a bearing under fluctuating loads, especially under loads whose direction varies from time to time, portions of bearing surface contacting the rotating shaft shift with the movement of axis of the shaft. At the peripheries of contact areas, tangential tensile stresses are produced, and in the center of the area, tangential compressive stresses. A frictional force causes tangential

compressive stresses in front of contact areas, and tensile stresses behind them in the sliding direction. The frictional heating also causes thermal stress. Thus the bearing metal is subjected to repeated tensile and compressive stresses due to the shifting of these contacting areas. These stresses are considered to be the main cause of fatigue failures in bearings.

Accordingly, the fatigue strength of bearing metals will be estimated in terms of the crack propagation rate of white metal lining on steel plate under plane bending. Further, the fatigue strength of metals is reduced by activity in environments⁽¹⁾. The fatigue strength of bearing metals will also be influenced by adsorption of lubricating oil and corrosion due to lubricating oil.

In the present paper, plane bending fatigue tests are carried out in lubricating oil, and the effects of lining thicknesses, operating temperatures, and the viscosities and activities of lubricating oil are discussed.

This study seems to make some contributions to the investigations of the fatigue strength of coating materials in general, as well as of that of plain bearing, and also of the crack rate affected by environments.

2. Fatigue strength of white metal lining on steel plate

2.1 Experimental procedure

White metal linings on one side of steel

* Received 10th July, 1964.

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plates with thickness of 2.25 mm were used as specimens. The shape and dimension of test pieces are shown in Fig. 1. The lining conditions and the chemical composition are in Tables 1 and 2. The micro-structures of the white metals are shown in Fig. 2. The A-specimen has smaller grain size of β -phase than the B-specimen because of the difference in cooling rate at the lining.

The test piece is fixed on the right side of AA in Fig. 1 and is subjected to reversed bending by rotating an unbalanced disc whose axis is situated at BB. The frequency is set at about 1 400 c/min. The surface strain ϵ_s is the nominal strain calculated elastically at the minimum section from the deflection of the test piece. In the calculation, it is assumed that the elastic modulus of white metal $E=5\,300\text{ kg/mm}^2$ and that of backing steel $E=21\,000\text{ kg/mm}^2$ are invariable for the temperature ranges of the present fatigue tests.

When a fatigue test is carried out at elevated temperatures, the side of the lining metal of the test piece is heated by an infrared ray lamp. The temperature of the surface of lining metal is controlled by measuring with thermo-couple. The

surface of lining metal is always covered with lubricating oil which is supplied from a nozzle at the rate of 2 cc per minute. In Table 3, total acid values of oils used are given.

2.2 Crack propagation

Fatigue cracks of test pieces are observed to originate from both edges of a circular hole where the maximum strain exists. The fatigue strength of white metal is lower than that of backing steel and cracks propagate gradually in the surface of white metal along the minimum cross section of the test piece as shown in Fig. 3(a). These cracks also develop within the white metal, and after arriving at the interface with the backing steel, they tend to propagate along this interface as shown in Fig. 3(b). The length of cracks at metal surface is measured by the micrometer microscope with a magnification of 50. For example, the relations between the cycle number n and the average length l of the cracks found on both sides of the circular hole of the A-specimens, tested in machine oil at the room temperature are shown in Fig. 4. The fatigue cracks propagate at a

Table 1 Lining conditions of tin-base white metal WJ2

Surface finishing of backing metal	Grinding
Pretreatment of backing metal	Degrease $\rightarrow$ Rinsing $\rightarrow$ Pickling $\rightarrow$ Rinsing $\rightarrow$ Neutralization $\rightarrow$ Hot rinsing $\rightarrow$ Tinning (twice)
Heat temp. of backing metal	250°C~300°C
Lining temp.	450°C
Lining method	Casting
Cooling	Natural
After treatment	Do-none

Table 2 Chemical composition of tin-base white metal

		Sn %	Sb %	Cu %	Pb %
JIS WJ 2	A-specimen	Bal.	8.47	5.53	1.03
	B-specimen	Bal.	8.10	5.43	0.05

Fig. 1 Shape and dimension of test pieces

A-Specimen
Magnification $\times 50$

B-specimen
Magnification $\times 50$

Fig. 2 Micro-structures of the lining metals

constant rate except in the vicinity of the circular hole. The reduction of cross section due to the growth of cracks is limited to within the lining metal and the increase of nominal strain is negligibly small. And it is considered that strain concentration at the tip of the crack is almost invariable for various crack lengths at the surface because the depth of a crack from the surface is kept constant. Therefore, the strain amplitude at the tip of the fatigue crack is approximately invariable regardless of the growth of the crack

Table 3 Total acid values of oils used after supplied from nozzle

Oil	Total acid value KOH-mg		
	Room temp.	80°C	150°C
Machine oil	0.08	0.08	0.08
Machine oil with oleic acid of 0.5%	1.39	—	1.33
Machine oil with oleic acid of 2.0%	5.07	5.08	5.00
Castor oil	2.45	2.48	2.42

Magnification $\times 2.6$

(a) Surface

Magnification $\times 60$

(b) Cross section

Fig. 3 Example of fatigue crack in white metal lining on backing steel

in lining metal and the fatigue crack propagates at a constant rate through the range having no strain concentration due to the circular hole.

The reciprocal of the stationary rate of crack propagation, U (n/mm), is obtained from Fig. 4 and the relation between U and ϵ_a is shown in Fig. 5. Fig. 5 is a kind of $S-N$ diagram for the crack propagation. Under the strain amplitude smaller than 4.7×10^{-4} in these testing conditions, a fatigue crack does not grow, or the number of cycles to growth of 1 mm crack length is more than 10^8 cycles, and this strain amplitude may correspond to the fatigue limit of materials having cracks.

Fig. 4 Relation between cycle number and average length of crack found on both sides of circular hole

Fig. 5 ϵ_a-U diagram in machine oil at room temperature

Fig. 6 Relation between strain amplitude and number of strain cycles to attain 1 mm length of crack

The relation between ε_a and the number of strain cycles N to attain 1 mm length of the crack is shown in Fig. 6. Fig. 6 may also correspond to a S - N diagram of white metal lining on steel plate with a circular notch. The strain at the fatigue limit is found to be 4.7×10^{-4} . The rotating bending fatigue strength ($N=1 \times 10^7$) for notched test pieces of WJ 2 white metal is about 0.4 kg/mm² in a solid form⁽²⁾ and the corresponding strain becomes 0.745×10^{-4} , assuming elastic modulus to be 5 300 kg/mm². The fatigue strength of the lining metal is considerably higher than that of the solid metal, even if the differences of testing conditions, such as stress concentration factors and whether in the oil or in the air, are taken into account. The cause of the difference in fatigue strength is considered to be the binding effect of the backing steel.

From these considerations, the crack propagation rate is used to estimate the fatigue strength of white metal lining on steel plate. From the ε_a - U diagram in Fig. 6, an empirical formula derived as follows.

$$\varepsilon_a U^\alpha = C \quad (1)$$

where, $\alpha=0.20$, $C=13.1 \times 10^{-3}$ for the A-specimen in machine oil at 25°C.

2.3 The effect of lining thickness on the fatigue strength

The life of plain bearing decreases remarkably as the lining thickness of bearing metal increases⁽³⁾⁽⁴⁾ and the decrease of life is attributed to the reduction of Brinell hardness⁽³⁾ and the variation of residual stresses in the lining metal⁽⁵⁾. In our experiments, too, the Brinell hardness increases as the lining thickness is decreased below about 0.3 mm, but the micro Vickers hardness remains constant over the cross section of the metal. The residual stresses in the test pieces used in our experiments show the maximum value at the surface and the values are 1.4~1.7 kg/mm² for each lining thickness⁽⁶⁾. Accordingly, it is considered

Fig. 7 Relations between crack length and cycle number for various lining thicknesses under constant amplitude of surface strain

that the residual stress and the Brinell hardness give little effect on the fatigue life of plain bearings.

Fatigue tests were carried out with the A-specimen of various lining thicknesses in machine oil at the room temperature under constant amplitudes of the surface strain. The relations between crack length l and cycle number n are shown in Fig. 7 for $\varepsilon_a=10.4 \times 10^{-4}$ and $\varepsilon_a=13.0 \times 10^{-4}$. From Fig. 7, the relations between $\log U$ and the lining thickness t_w are obtained linearly as shown in Fig. 8. The empirical formula is given as follows,

$$U = C_s e^{-t_w/\beta} \quad (2)$$

Further, a parallel relation for different strain amplitudes is observed in Fig. 8, and the value of β is found constant. The value of α in Eq. (1) is constant for various thicknesses of the lining metal. From Eqs. (1) and (2), we obtain,

$$U = (C/\varepsilon_a)^{1/\alpha} = C_s e^{-t_w/\beta}$$

$$C = \varepsilon_a C_s e^{-\alpha t_w/\beta} = C_t e^{-\alpha t_w}$$

Consequently

$$\varepsilon_a U^\alpha = C_t e^{-\alpha t_w}, \quad \alpha = \alpha/\beta \quad (3)$$

where $C_t=15.0 \times 10^{-3}$, $\alpha=0.268$ for A-specimens in machine oil at the room temperature.

While the crack propagation rate increases with the thickness of lining metal, the cycle number for the crack initiation is found almost the same for each lining thickness as shown in Fig. 7. The reduction of service life as the result of thickening the lining layer was sometimes attributed to the increase of surface strain under the same amount of deformation of bearing shells⁽⁷⁾. The present fatigue tests are carried out under constant surface strain amplitudes. So, it is considered that the reduction of fatigue lives of lining metals with an increase of thickness depends on the difference in the crack propagation rate.

Fatigue cracks grow in the lining metal alone

Fig. 8 t_w - U diagram for constant amplitude of surface strain

and the strain concentration is limited to the lining layer. Since the strain concentration at the tip of a crack is, however, lowered by the binding effect of backing metal which diminishes as the lining thickness increases, the crack propagation rate increases with the lining thickness. On the other hand, the effect of strain concentration also extends to the backing metal. When an excessive strain enough to cause fatigue cracks in the backing steel is applied, the fatigue crack propagates from the lining metal into the backing steel before the initiation of a crack at the back side of test pieces without lining where the strain amplitude is higher than at the interface.

When a stress concentration at the tip of a shallow notch is measured with the photoelastic method by a birefringent coating, the measuring error increases with the coating thickness⁽⁸⁾. From this, the effect of binding the strain by backing metal is also affirmed.

3. The effect of temperature and lubricating oil on the fatigue strength

3.1 The effect of temperature

The fatigue strength of the bearing metal was remarkably decreased when running temperature rose as seen from the results of endurance tests by a bearing testing machine⁽⁹⁾. It is considered that the thermal strain due to the difference of thermal expansion between the backing metal and the lining metal affects the fatigue strength as a mean strain, when the temperature rises. However, the effect of a mean strain may be rather small. The temperature effect is mainly in the change of the mechanical properties of bearing metals and the physico-chemical properties of lubricating oil

Fig. 9 Relations between strain amplitude and number of cycles to attain 1 mm length of crack

which always covers the metal surface.

The fatigue tests are carried out both in machine oil and castor oil at the room temperatures, 80°C, and 150°C by the same method as mentioned in the previous chapter. The lining metal of test pieces is A-specimen and the lining thickness is kept at 0.50 mm. The relations between the strain amplitude ϵ_a and the number of cycles to attain 1 mm length of the crack are illustrated in Fig. 9. The fatigue strength tends to lower as the temperature rises, and the inclination of a linear part of ϵ_a - N diagram increases with temperature, especially in castor oil. The evidence shows the time effect of corrosion and adsorption on the fatigue life of metals.

The relations between the reciprocal of crack propagation rate U and ϵ_a are shown in Fig. 10. The linear parts of all the curves remain parallel with each other. Accordingly, the value of α in Eq. (1) is constant and equal to 0.20, and the value

Fig. 10 ϵ_a - U diagram in machine oil and in castor oil

Fig. 11 Relations of fatigue strength vs. absolute temperature T

of C varies with the temperature. The fatigue strength of the metal affected by environments may be expressed by C . Fig. 11 shows the dependence of C on the absolute temperature T . The relation between $\log C$ and $1/T$ is linear. The change of C by temperatures in castor oil is larger than that in machine oil. The fact that the effect of oil temperature on the fatigue strength varies with various oils is due to the properties of oils varying with the temperatures.

For example, when the oil supply is decreased, a gush of bubbles is observed from the crack in the low viscosity machine oil as shown in Fig. 12. While in high viscosity castor oil, bubbles flow out intermittently. The phenomenon indicates that a lower viscosity oil comes into and out of the crack more easily than a higher viscosity oil, and that the viscosity of oil considerably affects the crack propagation rate. The higher fatigue strength in castor oil than in machine oil at the low temperature is considered due to its high viscosity, and the reverse at the high temperature may be caused by the activity of castor oil.

Further, the isolation of air by covered oil might have effect on fatigue strength. The fatigue test on the same test pieces was carried out in

the air without oil at the room temperature and at 80°C. Under the strain amplitude of $\epsilon_a = 10.4 \times 10^{-4}$, the values of U are obtained as 2.0×10^5 n/mm and 2.8×10^4 n/mm at 25°C and 80°C respectively. Substituting these results into Eq. (1), and assuming $\alpha = 0.20$, the values of C are calculated as 12.0×10^{-8} at 25°C and 8.1×10^{-8} at 80°C. The value of C in air is 8% less than in oil at 25°C, and 23% less at 80°C respectively. From these, the lubricating oil is seen to have played an important role in improving the fatigue life by preventing metal oxidization. And the fatigue strength decreased more sharply in air than in oil when the test temperature rose.

The dependence of C on temperature is expected from the viscosity and the activity of oil as well as the fatigue strength of the metal itself at the temperature. Experimental equations on the relation between C and $1/T$ are obtained as follows.

$$\begin{aligned} C &= 3.10 \times 10^{-8} e^{4.30 \times 10^2/T} \quad (\text{in machine oil}) \\ C &= 1.37 \times 10^{-8} e^{7.43 \times 10^2/T} \quad (\text{in castor oil}) \end{aligned} \quad \dots\dots\dots (4)$$

Eq. (4) contains the factors mentioned above, and is reduced to

$$C = C_0 \{f(T) \cdot g(\eta) \cdot h(c)\} \quad \dots\dots\dots (5)$$

where,

$1/f(T)$: Rate of varying the fatigue strength of white metal itself by temperature.

$1/g(\eta)$: Rate of varying the fatigue strength of white metal by viscosity of oil.

$1/h(c)$: Rate of varying the fatigue strength of white metal by activity in oil.

In order to find out the effects of these factors, it is necessary to know the values of $f(T)$, $g(\eta)$, $h(c)$ respectively.

3.2 The effect of viscosity

Magnification $\times 20$

Fig.12 Gushes of bubbles from the fatigue crack (in machine oil)

Table 4

Specimen	Oil	Testing temp. °C	Kinematic viscosity at testing temp. cSt	Total acid value KOH-mg	C_B	C_A
B	Spindle oil	23	13	0.05	10.0×10^{-8}	
	Machine oil	23	100	0.08	12.0	
	Motor oil	27	340	0.20	13.8	
A	Machine oil	25	90	0.08	(12.0)	13.1×10^{-8}
	Castor oil	20	1200	2.45	(15.0)	16.6
	Castor oil	5	4000	2.45	(18.1)	20.0

C_B shown in brackets is the value of B-specimen in the castor oil which is calculated from the value of C of A-specimen in the castor oil using the ratio of C_B to C_A in machine oil

The fatigue tests were carried out at the room temperature in pure mineral oils of various viscosities to find out the effect of viscosity. Spindle oil, machine oil, and motor oil are used with no additives. The viscosity and the total acid values of oils are shown in Table 4. B-specimens with lining thickness 0.50 mm are used. Fig. 13 illustrates relations between ϵ_a and U . The straight portions in the ϵ_a - U diagram of B-specimen are parallel with each other for various oils and have the same gradient as those of A-specimen. So, the effect of viscosity on the fatigue strength is also estimated by the value of C in Eq. (1). The values of C are shown in Table 4. In the table, C_A and C_B represent the values of C on A-specimen and B-specimen respectively. C_B is found about 8% less than C_A in machine oil because the grain of β -phase in the former is more coarse than that of the latter. C_B shown in brackets is the value of C of B-specimen in the castor oil which is not given by tests but is calculated from the value of C of A-specimen in castor oil using the ratio of C_B to C_A in machine oil.

The relation between C_B and kinematic viscosity η is shown in Fig. 14, where the effect of activity in castor oil is considered to be small at the room temperature. As is seen in Fig. 14, C increases with viscosity. It has been known that

Fig. 13 ϵ_a - U diagram in pure mineral oils of various viscosities at the room temperature

Fig. 14 Effect of viscosity of oil for the fatigue strength

the tests by a bearing testing machine made in high viscosity oil gave us more desirable results than that in low viscosity oil under the same temperature⁽¹⁰⁾.

The reason why fatigue crack propagation is affected by viscosity of oil may be clarified by an analysis on the behaviour of oil in the crack. When the test piece is subjected to compressive stress, the oil which has penetrated in the crack during the tensile stressing increases in pressure. If the crack closes with velocity V , the pressure increment p at the tip of crack is expressed by

$$p = (6\eta V/h^3)l^2 \dots \dots \dots (6)$$

where, l is crack length, h is width of crack and η is viscosity as is shown in the model of a crack in Fig. 15. The tensile strain due to the oil pressure is superposed at the tip of crack during compression and the total compressive strain at the tip of crack is decreased. During tension, there is no variation of strain produced by oil. Therefore, under reversed strain, the actual strain amplitude decreases as p increases, and the fatigue strength is heightened with the viscosity of oil. On the other hand, the facility of oil penetration into the crack is related to

$$\phi = \gamma \cos \theta / 2\eta \dots \dots \dots (7)$$

where, γ is surface tension, and θ is contact angle between oil and metal. It is understood that oil tends to be harder to penetrate into crack as the viscosity increases, and the increasing rate of fatigue strength is reduced in the oil of higher viscosity as is seen in Fig. 14.

The relation between $\log C$ and $\log \eta$ is proportional in the range of viscosities tested now. The experimental equation for C as expressed by η is as follows

$$C = 7.65 \times 10^{-3} \eta^{0.28} \dots \dots \dots (8)$$

From Eq. (5) and Eq. (8)

$$g(\eta) = 1.58 \eta^{-0.28} \dots \dots \dots (9)$$

is obtained if $C = 12.0 \times 10^{-3} (=C_m)$ in machine oil at 23°C ($\eta = 100$ cSt) is taken as a basis.

Fig. 15 Model of a crack

3-3 The effect of activity of oil

The fatigue strength of steel is lowered by activity of oil, and the adsorption fatigue is introduced⁽¹⁾ where fatigue strength decreases with the surface energy of the metal. In the present study, the effect of activity in castor oil is also expected because of the difference of fatigue strengths in castor oil and in machine oil at elevated temperatures.

The fatigue tests are carried out in machine oil added with 0.5% and 2.0% oleic acid at the room temperature, 80°C and 150°C. The test piece is of B-specimen and the lining thickness is kept at 0.50 mm. Total acid values of oils are given in Table 3. The relations between U and ϵ_a are shown in Fig. 16. As the linear parts in these curves can be recognized as parallel with each other, only the value of C in Eq. (1) is varied with oils and temperatures. The dependence of $\log C$ on $1/T$ is shown in Fig. 17. In the figure, the value C of B-specimen in pure machine oil and castor oil (solid lines) are the calculated values from the value C of A-specimen in those oils (dotted lines) using the ratio of C of A-specimen to that of B-specimen in machine oil at the room

Fig. 16 ϵ_a - U diagram in machine oil with oleic acid of 0.5% and 2%

temperature. The variations of C with temperature are caused by factors presented in Eq. (5). Using Eq. (9), we can remove the effect of viscosity varying with temperatures. The values of C obtained from Fig. 17 and the value of C calculated under the constant viscosity of 100 cst at various temperatures are plotted in Fig. 18 in fraction of C_m .

In Fig. 18, ΔC_η shows the effect of viscosity $1/\eta(\eta)$, and ΔC_T is the varying ratio of fatigue strength due to other than viscosity, that is equal to $1/f(T)h(c)$. Assuming that the fatigue strength is not affected by the activity in machine oil, the line for $\eta_0=100$ cst in Fig. 18(a) represents the fatigue strength of lining metal itself at various temperatures, and is expressed in the form $C=B \exp(b/T)$.

Hence, on the basis of C_m (at 23°C in machine oil where η is 100 cst), $f(T)$ is obtained from Eq. (5) as

Fig. 17 Relations of fatigue strength vs. absolute temperature T

Fig. 18 Relations of fatigue strength vs. absolute temperature T

$$f(T) = 1.45 \exp \{-1.08 \times 10^2 / T\} \quad \dots\dots\dots (10)$$

where $g(\eta) = 1$, $h(c) = 1$.

ΔC_T in Fig. 18(b), (c) and (d) include both the terms $f(T)$ and $h(c)$. The effect of activity, $h(c)$, is given by using Fig. 17 and Eq. (5), Eq. (9) and Eq. (10). Fig. 19 shows the relation of $\log h(c)$ and $1/T$. When obtaining $g(\eta)$, the effect of activity in castor oil at the room temperature was ignored, and $h(c)$ should be drawn as dotted line for castor oil. The experimental equation is given by

$$h(c) = K \exp \{-k/T\} \quad \dots\dots\dots (11)$$

Where K and k are the constants concerned with kinds of oil and concentrations of oleic acid. Fig. 20 shows the relation between total acid value and $h(c)$. The marks $\bullet$ in Fig. 20 show the values of castor oil amended by the dotted line in Fig. 19; $h(c)$ of castor oil is lower than that of machine oil added with oleic acid under the same acid values. The discrepancy seems to be due to the difference of chemisorption of free fatty acids in castor oil and in machine oil.

Table 5 shows the adsorption energy of oil on the surface of white metal finished with emery paper and the surface tension of oil. The adsorption energy of machine oil increases with the concentration of oleic acid, but the value of castor oil does not vary by adding 1% oleic acid. The concentration of free fatty acid in this oil is almost the same as that in machine oil added with 2% oleic acid. The physical adsorption is more intense in castor oil whose main composition is glycerin ester than in machine oil whose main composition is hydro-carbon. The physical adsorption is considered to hinder the chemisorption of fatty acid. Although the adsorption energy may be different slightly between the surfaces finished by emery paper and the new surfaces of fatigue cracks, the difference of $h(c)$ in machine oil and in castor oil is explained by the chemisorption of free fatty acid which is reduced by the physical adsorption.

The effect of frequency of reversed strain on the activity is studied through the test made in machine oil added with 2% oleic acid at 150°C.

Fig. 19 The effect of activity in oils vs. temperature

$U = 5.0 \times 10^4 \text{ n/mm}$ is obtained under $\epsilon_a = 4.12 \times 10^{-4}$ at 1150 c/min, and $U = 6.1 \times 10 \text{ n/mm}$ under $\epsilon_a = 2.41 \times 10^{-4}$ at 770 c/min respectively. Substituting the results into Eq. (1), $C = 3.6 \times 10^{-3}$ for 1150 c/min and $C = 2.2 \times 10^{-3}$ for 770 c/min are obtained, taking $\alpha = 0.20$. The crack propagation rate increases as the frequency is lowered, and it is found that the frequency also affects the variation of fatigue strength due to the activity of oil.

In conclusion, the effects of temperature, viscosity of oil and activity of oil are studied quantitatively. Taking $C = 12.0 \times 10^{-3}$ at 23°C in machine oil as a basis, Eq. (5) is reduced to

$$C = 12.0 \times 10^{-3} C' \exp \{1.08 \times 10^2 / T + 0.23 \log \eta + k/T\} \equiv F(1/T) \quad \dots\dots\dots (12)$$

where, C' is a constant. Since the viscosity in the second term is a function of $1/T$, Eq. (12) depends only on the temperature, and the meaning of the constants in Eq. (4) are well known.

4. Conclusion

The fatigue tests of white metal lining on steel plate are made in the lubricating oil to make clear the unknown factors affecting the fatigue life of bearing metals under varying loads. Since the fatigue crack propagates on lining metal at a constant rate except for the early stage of crack initiation, the fatigue strength of the bearing metal is studied as the crack propagation rate, and

Table 5 Adsorption energy of oil on the surface of white metal finished with emery paper and the surface tension of oil

Oil	Adsorption energy erg/cm ²	Surface tension dyn/cm
Machine oil	56.2	30.5
Machine oil with oleic acid of 0.5%	58.2	30.6
Machine oil with oleic acid of 2.0%	60.0	30.8
Castor oil	61.1	33.0
Castor oil with oleic acid of 1.0%	61.4	33.3

Testing temp. 20°C

Fig. 20 The effect of activity in oils and total acid value

the following are known.

(1) Below a certain nominal strain amplitude in lining metal surface, the fatigue crack does not grow. The fatigue limit is found for the lining white metal having cracks.

(2) The fatigue strength is reduced as the lining thickness increases, because of the difference in the binding effect of the strain at the tip of fatigue cracks between the lining metal and the backing steel.

(3) The fatigue strength of white metal is lowered when the grain size of β -phase is large.

(4) The dependence of fatigue strength on temperature is expressed by the equation $C=F(1/T)$ and is affected by viscosity and activity of the lubricating oil.

(5) The reduction of fatigue strength of lining metal itself at high temperatures is lower in oil than in air.

(6) The lubricating oil insulating the metal surface from the air heightens the fatigue strength.

(7) The dependence of fatigue strength on the viscosity of lubricating oil is due to the oil pressure in the wedge of the crack where the oil penetrates according to its viscosity.

(8) The reduction of fatigue strength due to the activity of oil may be caused mainly by the chemical adsorption at the tip of crack. Accordingly, the effect of activity differs by the concen-

tration of free fatty acid, temperature, kinds of oil and frequency of reversed strain.

Acknowledgement

The present study is a part of the research sponsored by the Subcommittee on Cross-Head Pin Bearing in Japan Soc. Mech. Engrs. Thanks are due to Mr. T. Ikeda for his cooperation, and also due to Mr. T. Matsunaga, Hitachi Shipbuilding & Engineering Co. Ltd., for the manufacturing of test specimens.

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Errata (Vol. 8, No. 31, August, 1965)

Author	Page	Column	Line	For	Read
T. HARA	392	Eq. (7)		$\dots \frac{c_f s x}{A-a} = \left\{ \left(1 + \frac{u_2}{U} \right)^2 + \dots \right.$	$\dots \frac{c_f s x}{A-a} \left\{ \left(1 + \frac{u_2}{U} \right)^2 + \dots \right.$
	"	right	2 from bottom	u_2/U	ϕ
	"	Fig. 2	ordinate	K	ϕ
	394	left	8	medel	model