Erosion Damages of Sintered Metals*

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In the present paper, erosion tests are carried out by vibrating a disc at the free end of a magnetostrictive oscillator close to the surface of sintered metals in water or in oil. The damages are due to fatigue by the collapse pressure of cavitation bubbles under a thick liquid film and due to fatigue by the surface shearing of a squeezed film under a thin liquid film. The thickness of liquid film showing the maximum value of the weight loss which is due to cavitation erosion, is larger on the sintered metal of higher porosity, because the porous surface of the sintered metal is easily filled with cavitation bubbles. The resistance to the erosion damages of sintered iron is lower than that of mild steel, and increases with smaller porosity, being proportional to the square of Brinell hardness. The resistance to the erosion damage of sintered copper-lead alloy of low porosity is considerably higher than that of lining copper-lead alloy. The fall-off particles of the former are very small compared with those of the latter. The resistance of high porosity alloy is also higher than that of the lining alloy when the film thickness is small.

1. Introduction

Recently, sintered metals are extensively used for bearings, gears, etc. In the plain bearings under fluctuating load or spur gears, two surfaces close and separate rapidly to and from each other through the medium of a thin oil film, and occasionally suffer erosion damages. These damages have been discussed in our previous studies^{(1) (2)}. The erosion tests were carried out by vibrating a disc at the free end of a magnetostrictive oscillator in close proximity to the steel plate or the plane surface of bearing alloy lining on steel plate in water or in lubricating oils.

As the result, it has been found that the damages are mainly caused by the collapse pressure of cavitation bubbles under a thick liquid film and by the shearing force of squeezed film under a thin liquid film, and the latter causes fatigue cracks in the lining alloy which lead to a catastrophic failure of bearings followed by flaking off from the back metal. Therefore, these damages are not made clear by discussing the resistance to cavitation erosion alone which is now rather well known. Further, the sintered metals are considered to show more complexities because of their porous surface.

In the present paper, sintered irons having various porosities are tested in water by vibrating

a disc near their surfaces, and the results are compared with those of the steel plate with the same chemical compositions. Further, the sintered copper-lead alloy is tested to clarify the mechanism of the damages due to thin oil film.

2. Test procedures

2.1 The testing apparatus

A schematic view of the testing apparatus is shown in Fig. 1, its details were described in the previous paper⁽¹⁾. A vibrating disc ④ of 20 mm diameter and 6 mm thickness is screwed to the free

① High frequency power source
② Oscillator
③ Horn
④ Disc
⑤ Plane test piece
⑥ Level stand
⑦ Container
⑧ Dial gauge
⑨ Leveling screw
Fig. 1 Schematic view of testing apparatus

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end of the horn ③. The disc is made of 18-8 stainless steel. The plane test piece ⑤ is fixed on the level stand ⑥ having the leveling screws ④ at a small parallel distance from the disc surface. The thickness h of liquid film between plane test piece and disc is measured by a dial gauge ⑧. The resonance frequency is 22 kc/sec, and the amplitude A_0 at the vibrating disc surface is 20 microns.

Water or oil is circulated to the container ⑦ through the cooling bath to keep the testing temperature constant. The temperature of liquid film, however, rises rapidly regardless of the constant temperature in the container. For instance, the film temperature at the center of the disc under the film thickness $h=0.2$ mm rises to 55°C in the water and to 195°C in the spindle oil, as was shown in the spindle oil, as was shown in the previous paper⁽¹⁾.

2.2 The test piece

Sintered irons are made of spongy Höganäs iron powders MH-100 (Fe: 98 %, C: <0.1 %, O: <0.8 %, S: 0.15 %, P: 0.015 %), and are sintered for one hour in hydrogen gas of 1120°C. The porosities V_p of the test pieces are controlled to 0.284 [density $\rho=5.65$ g/cm³, Brinell hardness $H_B(10/500/30)=50$], 0.263 ($\rho=5.81$ g/cm³, $H_B=55$), 0.226 ($\rho=6.10$ g/cm³, $H_B=67$) and 0.163 ($\rho=6.60$ g/cm³, $H_B=104$). The sintered bearing alloy is made of copper-lead alloy powders (Cu: 70 %, Pb: 30 %) obtained by atomizing, and is sintered for one hour in hydrogen gas of 780°C. The porosity V_p is 0.100 ($\rho=8.70$ g/cm³, $H_B=11.2$). The other test piece is made by pressing after sintering and its porosity

is 0.033 ($\rho=9.35$ g/cm³, $H_B=35$).

Figure 2 shows the shape of powders before the sintering. Figure 3 shows the surfaces after the sintering which are finished with a diamond paste. Many pores are observed in the surfaces. The test pieces of these metals are 4 mm thick and their testing surfaces are finished with #0/2 emery paper.

3. Experimental results and discussion on sintered irons

3.1 The feature of erosion damages

Figure 4 shows the surfaces of sintered iron and 0.09 %C carbon steel eroded in water under the thickness of $h=0.2$ mm. The erosion damages of both the materials occur around the periphery of the circular area which is almost the same as the area of the disk, and propagate to the central parts of the circle. The damages of the periphery become also more intensive with the progress of the tests. But the damaged surface of sintered iron is more uneven than that of the steel. As will be shown in Fig. 8 and Fig. 9, the weight loss of the former is also larger than that of the latter under large liquid film thickness where the damages are mainly caused by the collapse pressure of cavitation bubbles.

Figure 5 shows microscopic photographs of the damaged surfaces of sintered iron. In the early period, small pits are concentrated as a network along the pores existing on the surface. Some parts of the surface are not yet damaged. In the stationary period, the pits spread over the surface and

(a) Höganäs iron powders, average diameter $d_m=37.3\mu$

(b) Copper-lead alloy powders, average diameter $d_m=18.3\mu$

Fig. 2 Shapes of powders before pressing

(a) Sintered iron, $V_p=0.284$

(b) Sintered copper-lead alloy, $V_p=0.100$

Fig. 3 Conditions of the surfaces polished with DP-diamond paste after sintering

(a) Sintered iron, $V_p=0.284$, $h=0.2$ mm, $A_0=20\mu$, Test duration=8 hrs, Total weight loss=118 mg

(b) 0.09 % C carbon steel, $h=0.2$ mm, $A_0=20\mu$, Test duration=8 hrs, Total weight loss=115 mg

Fig. 4 Damages of sintered iron and carbon steel in water

(a) Initial period of erosion, test duration 1 hr

(b) Stationary period of erosion, test duration 5 hrs
Fig. 5 Microscopic photographs of the damaged surfaces of sintered iron

at the same time the pits along the pores grow to large pits. So, the resulting surface is more uneven than that of the steel as shown in Fig. 4. An example of particles falling off into the water is shown in Fig. 6. The particles are considerably smaller than the original powders before sintering. Consequently, small pits are not considered to result from the falling off of original powders but from the cracks propagating through the powders.

At a thin film thickness, damages are found to grow in the radial direction at the periphery as shown in Fig. 7. In the previous papers^{(1) (2)}, radial fatigue cracks were found in the bearing alloy lining on steel plate, and progressed to flaking of lined alloy from the backing steel by the repeated high surface stresses at the periphery. The damage shown in Fig. 7 is considered due to the propagation of fatigue cracks and also to the flow corrosion at the active surfaces caused by the fatigue failure.

The test piece is weighed after dehydrating it in the vacuum of 10^{-5} mmHg at $100^\circ\text{C} \sim 130^\circ\text{C}$ for

$V_p=0.284$, $h=0.1$ mm, Average diameter $d_m=8\mu$
Fig. 6 Particles of sintered iron falling off into water

$V_p=0.284$, $h=0.1$ mm, $A_0=20\mu$, Test duration=8 hrs, Total weight loss=174 mg
Fig. 7 Damages of sintered iron grown up in the radial direction at the periphery in water

90 minutes and cooling to the room temperature. The results are shown in Fig. 8. The weight loss of the sintered iron is proportional to the exposure time at the stationary period. So, the erosion resistance of the test piece will be discussed with the stationary rate of weight loss w .

3.2 The effects of porosity on erosion damages

The dependence of w on the film thickness h is shown in Fig. 9 for the sintered irons with the porosities $V_p=0.284$ and $V_p=0.163$. The figure also shows the w of 0.09% C steel. As the film gets thinner, the w increases and diminishes after passing a maximum value. The former increase is due to the increase in the number of cavitation

Fig. 8 Weight loss of test pieces

Fig. 9 Dependence of the stationary rate of weight loss w on the film thickness h

bubbles arriving at the surface of the test piece from the vibrating disc, and the latter decrease is due to the accumulation of bubbles with the decrease of film thickness.

The thickness showing the maximum w is larger on the sintered iron than on the carbon steel and it gets greater with higher porosity, because many pores in the surface tend to be easily filled with cavitation bubbles and the fixed-type cavitation occurs at relatively larger film thickness. For the same reason, the thickness showing the maximum w is larger on copper-lead alloy than on tin-base white metal as was explained in the previous paper.

At smaller thickness, the value of w rises again on the sintered iron with the larger porosity of $V_p=0.284$ owing to the fatigue damages due to the repeated shearing stresses at the periphery as shown in Fig. 7. The same phenomena were found on the bearing alloys tested in lubricating oils. On the sintered iron with the smaller porosity of $V_p=0.163$ and the carbon steel, too, the rising must appear at still smaller thickness.

Additional tests are carried out on the sintered irons of $V_p=0.266$ and 0.263 . The relation between the reciprocal of rate of weight loss $1/w$ and the porosity V_p is obtained at the thickness more than $h=0.4$ mm where the cavitation is main cause of the erosion damages as is shown in Fig. 10. The curve in the figure gives the following empirical formula.

$$1/w_{0.4} = 1.46 \times 10^{-3} \{(1-V_p)/V_p\}^2 \quad (1)$$

The relation between the porosity V_p and the tensile strength σ_B is presented in consideration of the stress concentration by the pores⁽³⁾ as

$$\sigma_B \propto (1-V_p)/V_p \quad (2)$$

The resistance to erosion damages is proportional to

Fig. 10 Effect of porosity on the erosion damages of sintered iron

the square of tensile strength from Eq. (1). When the static strength corresponds to Brinell hardness H_B , the dependence of $1/w_{0.4}$ on the H_B is given from Fig. 11 as follows.

$$1/w_{0.4} = 3.62 \times 10^{-6} H_B^2 \quad (3)$$

Previously, one of the authors⁽⁴⁾ proposed the following relation between the resistance to cavitation erosion and the elastic strain energy of the materials.

$$1/w \propto H_B^2/E \quad (4)$$

The elastic modulus E_p of the sintered metal⁽⁶⁾ is given by $E_p = E_0(1 - V_p)$, where E_0 is the elastic modulus of sintered metal with the porosity $V_p = 0$. The dependence of $1/w_{0.4}$ on $H_B^2/(1 - V_p)$ is obtained as a straight line passing the zero point as shown in Fig. 12. The relation is presented by

$$1/w_{0.4} \propto H_B^2/E_0(1 - V_p) = H_B^2/E_p \quad (5)$$

It is not clear which of H_B^2 and H_B^2/E is more contributing to the erosion damage because the variation of the elastic modulus is smaller than that of H_B in the tested range of porosities. However, it is considered that the erosion resistance is proportional to the square of the Brinell hardness, and this may be proper from the view point that cavitation erosion is caused by the impact energy of liquid to the metal surface.

3.3 The size of particle falling off into water

The sizes of original powders before sintering and of particles falling off into water after erosion test distribute as in Table 1. The sizes are measured by a microscope in terms of unidirectional lengths. The average diameter d_m and the standard deviation σ

are the values for three hundred particles in one lot. The particles falling off into water are generally smaller than those before sintering. Especially, a lot of falling off particles includes many particles smaller than five microns in the diameter. It is understood that the erosion of the sintered iron is not due to falling off of the original powders but is due to breaking to small pieces by crack propagation.

In Table 1, differences of d_m for various test conditions are recognized under the significance level of 0.1% error by means of F-test and Cochran-Cox method. At large film thickness, both d_m and σ are large, because the collapse pressures of cavitation bubbles are repeated as Hertzian stresses and relatively large particles are produced by the subsurface fatigue cracks. At small film thickness, d_m and σ become small because of the surface failures by the repeated shearing forces of squeezed film. Also, both d_m and σ become larger with higher porosity which makes it easy to break the inside materials. On the mild carbon steel, however, no difference of d_m and σ is recognized between thicknesses $h = 0.1$ mm and $h = 0.4$ mm under the significance level of 0.1% error, though the particle sizes are found greater than those of sintered metals. Therefore, it is considered that the erosion particles of mild carbon steel are produced by the propagation of the transcrystalline fatigue cracks.

4. Experimental results and discussion on sintered copper-lead alloys

4.1 The feature of erosion damage

Erosion tests are carried out in pure spindle oil

Fig. 11 Relation between the erosion damage of sintered iron and its hardness

Fig. 12 Relation between the erosion damage of sintered iron and its hardness

on the sintered copper-lead alloys of the porosities $V_p=0.33$ and $V_p=0.10$ to compare with the cast copper-lead alloy. Surface damages are photographed as shown in Fig. 13. The feature of macro-damages is similar to that of sintered iron tested in water and of copper-lead alloy lining on steel plate in tested spindle oil described in the previous paper⁽³⁾.

Particles falling off into the spindle oil are shown in Fig. 14 (a). These particles are more uneven and smaller than the original powders before sintering shown in Fig. 2. The average diameter d_m of the original powders is 18.3 microns, while that of particles falling off from the test piece having the porosity $V_p=0.033$ tested at the film thickness $h=0.4$ mm is 11.8 microns. It is considered

in this case too, that erosion damages are not caused by falling off of the original powders but by tearing of small particles produced by crack propagation. On the lining copper-lead alloy, the cracks propagate in networks of lead and particles falling off into the oil are massive lumps composed of copper and lead as shown in Fig. 14 (b). Consequently, the weight loss of sintered copper-lead alloy is smaller than that of lining copper-lead alloy as will be discussed latter. These results contradict the relation between sintered iron and mild steel mentioned before.

Table 1 Distributions of the particle sizes of sintered irons and carbon steel falling off into water (Measuring number=300 particles)

	Original powders before sintering	$V_p=0.284$		$V_p=0.163$		0.09 % C steel	
		$h=0.1$ mm	$h=0.4$ mm	$h=0.1$ mm	$h=0.4$ mm	$h=0.1$ mm	$h=0.4$ mm
~5	15	204	153	238	217	117	84
~10	56	55	77	47	43	28	42
~15	40	16	22	7	4	23	60
~20	40	3	6	3	6	26	59
~25	27	5	3	2	2	26	27
~30	18	3	3	1	5	18	10
~35	16		3	2	6	11	3
~40	4	3	4		7	9	3
~45	6	2	2		3	13	6
~50	3	3	1		1	8	2
~60	8		4		4	12	
~70	9	3	1		2	2	
~80	8	1	2			1	1
~90	7		3			3	1
~100	11		3				1
~110	6		3			1	1
~120	6		3			1	
~130	7	1	3				
~140	5						
~150	3	1	2				
~160	3		1				
~170	1		1			1	
~180	1						
Average diameter d_m	37.3	8.0	15.3	4.6	7.7	18.1	13.5
Standard deviation σ	39.5	14.2	28.1	3.9	11.2	22.0	12.8

$V_p=0.033$, $h=0.2$ mm, $A_0=20\mu$, Test duration=3 hrs, Total weight loss=66 mg

Fig. 13 Damages of sintered copper-lead alloy in spindle oil

(a) Small particles of sintered copper-lead alloy

(b) Massive particles of lining copper-lead alloy

Fig. 14 Particles falling off into spindle oil

4.2 The effect of porosity on erosion damages

Relations between the rate of weight loss w in pure spindle oil and the film thickness h are shown in Fig. 15 on sintered copper-lead alloys of $V_p=0.033$ and $V_p=0.100$ and on copper-lead alloy lining on steel plate [lining thickness $t_M=0.50$ mm, $H_B(10/500/30)=26$]. The weight loss of sintered copper-lead alloy is measured after washing perfectly in benzene and drying in hot air. The dependence of w on h shows the same tendency as the steel and the bearing alloys tested in water or in oil shown in the previous paper. As the oil film becomes extremely thin, the value of w rises again owing to the repeated shearing forces of squeezed film. In this case too, damages in the radial direction are observed at the periphery of eroded circle.

The thickness showing the maximum value of w on the sintered copper-lead alloy with very small porosity like $V_p=0.033$ is equal to that on the lining copper-lead alloy, but is smaller than that on $V_p=0.100$. As mentioned before, this is caused by the fixed-type cavitation which is more easily reached when the surface is more porous. Therefore, the surface of lining copper-lead alloy is considered to have the same unevenness as the surface of sintered copper-lead alloy with $V_p=0.033$ because of falling off of the massive metals.

The w of sintered copper-lead alloy with small porosity is about a half that of lining copper-lead alloy, because the particles falling off from the former alloy is very small. However, the w of sintered copper-lead alloy with large porosity is almost the same as that of the lining alloy due to the lower hardness when the tests are made under oil film thicker than the thickness showing the maximum w , but becomes less than the latter at the thin film thickness because the fixed-type cavitation is reached more easily on account of its more uneven surface.

For an extremely thin oil film, the rates of

weight loss is in the order of the sintered copper-lead alloy of $V_p=0.100$ (Brinell hardness $H_B=11.2$), the lining copper-lead alloy ($H_B=26$) and the sintered copper-lead alloy of $V_p=0.033$ ($H_B=35$). The erosion resistance is in accordance with the Brinell hardness, showing that the failure is due to the repeated mechanical stresses.

5. Conclusions

To study erosion damages of sintered metals, tests are carried out in water or in oil by vibrating a disc at the free end of a magnetostrictive oscillator in close proximity to the surface of test piece. The following conclusions are obtained.

(1) The rate of weight loss w of sintered metals increases with smaller film thickness due to the increase of damages by the cavitation erosion, and decreases after passing a maximum value due to the fixed-type cavitation. The thickness showing the maximum value of w increases with larger porosity because the fixed-type cavitation is reached more easily.

(2) At very small film thickness, damages are found to grow in the radial direction at the periphery of damaged area owing to the fatigue by the repeated shearing stresses.

(3) The particles of sintered iron falling off into water are smaller than the original powder before sintering. The erosion resistance of sintered iron is lower than that of the steel of nearly the same chemical compositions, and decreases with the higher porosity. The resistance is proportional to the square of Brinell hardness.

(4) The falling off particles of the sintered copper-lead alloy are very small in size compared with those of the lining copper-lead alloy. The resistance of the sintered alloy of small porosity is considerably higher than that of the lining alloy. When the porosity is large, the resistance becomes nearly equal to the latter under thick oil film, but is higher than the latter under thin oil film.

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Fig. 15 Dependence of the stationary rate of weight loss w on the film thickness h