Scoring Resistance of Spur Gears with Various Coatings *

(2nd Report, Scoring Tests under Dry Friction)

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To examine the scoring resistance of spur gears with various coatings under dry friction, scoring tests on gear pairs coated with copper, graphite, zinc, molybdenum disulfide and phosphate were carried out under dry friction using a power-circulating gear machine. Further, variation in the bulk-temperature of the gear tooth was measured by a thermocouple embedded in the side of the tooth. From the experimental results a significant effect of copper and graphite on the scoring resistance under dry friction was recognized. The bulk-temperature of the gear tooth dropped after the initial stage of scoring for all gear pairs.

Key Words : Gear, Scoring Resistance, Coatings, Dry Friction, Solid Lubricant, Bulk-temperature

1. Introduction

In a previous report⁽¹⁾, the scoring resistance of gears with various coatings was clarified under forced lubrication. In gear transmissions, however, there are some cases when gears are running under nearly dry friction. For example, in the transmissions of a helicopter, there is a case when the gears are running under dry friction due to a trouble in the supply system of a lubricating oil. In such a case, time until the gears can not run due to the occurrence of a scoring failure is an important problem. With respect to the performance of the gears with coatings under dry friction, there are investigations on copper-plating⁽²⁾ and MoS₂ coating⁽³⁾.

In this report, scoring tests were carried out under dry friction for the same gear pairs as in the previous report and the life of the gears up to the occurrence of a scoring failure was examined. Further, the variation in the bulk-temperature of the tooth of the wheel was measured by a thermocouple embedded in the side of the tooth, and the behavior of the occurrence and the progress of a scoring failure was clarified.

2. Experimental Method

2.1 Test gears

As mentioned in the previous report, test gears were made of SCM415H, and they

were ground by a Reishauer gear grinding machine after gas-carburizing. Table 1 shows specifications of the test gears. Scoring tests were carried out on the gear pairs of which the pinions and the wheels were coated with the same materials. The coating treatment of the test gear pairs is described in Table 2.

2.2 Test conditions and methods

As for test conditions, using a power-circulating gear machine, the gears were run at a rotational speed of pinion $n_p = 4655$ rpm at a normal load per unit face width of $P_n = 266$ N/mm. The tests were carried out for 10 min under forced lubrication with #140 turbine oil which was a straight mineral oil without additives. In this case, the oil was sprayed onto the meshing faces at a rate of 0.6 L/min and then its temperature was controlled to 323 ± 2 K. After that, the supply of the oil was completely stopped. Then, the tests were continued under nearly dry friction until the gears could not run due to the occurrence of a destructive scoring failure.

Table 1 Specifications of test gears

	Pinion	Wheel
Number of teeth z	18	40
Center distance mm	116	
Pressure angle α_0	20°	
Module m mm	4	
Backlash S_n mm	0.5	
Face width B mm	10	
Effective face width B_f mm	7	
Tooth profile	Standard	
Pitch circle diameter d_0 mm	72	160
Outside diameter d_1 mm	80	168
Contact length mm	19.15	
Contact ratio ϵ	1.62	
Material	SCM 415H	

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Table 2 Coating treatment of test gear pairs

Gear pair	Surface treatment
C	Cu-plating
G	Graphite coating
Z	Galvanizing
U	Uncoated
M	MoS ₂ coating
P	Phosphate coating

Fig.1 Measurements of bulk-temperature and dynamic strain at compression side of tooth fillet

Scoring was detected by extreme variations in the gear noise, acceleration due to oscillation of a test gear box and the bulk-temperature of a tooth of the wheel. As for the measurement of the bulk-temperature of the wheel, as shown in Fig. 1, a hole which was 2 mm in diameter and 3.5 mm in depth was drilled on the side of the tooth of the wheel (at the center of the tooth on a pitch circle), and a CA-thermocouple in a teflon tube was embedded in the hole. The thermoelectromotive force during the tests was measured through a slip ring and recorded on a pen recorder.

As an example, in the case of the test for gear pair P (phosphate coating), a dynamic strain at the compression side of the tooth fillet of the wheel was measured, and the relations between the

dynamic strain and the bulk-temperature of the wheel, the gear noise and the oscillation of the gear box were estimated. In this case, as shown in Fig. 1, a strain gauge was stuck to the compression side of the tooth fillet of the wheel. The output was measured through the slip ring and recorded on a data recorder.

3. Test Results and Discussion

3.1 Bulk-temperature of gear tooth

Figure 2 shows the variation in the bulk-temperature of the wheel for the cases of gear pairs C, G, U and P. In these cases, a lubricating oil was supplied for 10 min from the start of the running. After that, the supply of the oil was completely stopped, and then the gears were run under nearly dry friction. The symbol S indicates that a destructive scoring failure occurred and that, just at that time, the test machine was stopped.

As evident from this figure, the variation in the bulk-temperature of the wheel makes a very interesting behavior. That is, for all gear pairs, the value of the bulk-temperature reached nearly stationary state after 1 min of the start of the running and the state continued until the oil supply was stopped. However, the bulk-temperature considerably rose just after the oil supply was stopped, and then its value reached a peak. After that, although the bulk-temperature slightly dropped (or did not rise), it rapidly rose again. Finally, a destructive scoring failure occurred, and then the gears could not run. Just before the test machine was stopped, white smoke arose from the test gear box and the rotational speed of the gears considerably decreased.

As for the life up to a destructive scoring failure, gear pair C (Cu-plating) endures the longest of all gear pairs. In contrast, gear pair U (uncoated) has the shortest life. The value of the bulk-temperature of gear pair P is considerably higher than that of the other gear pairs. When a destructive scoring failure occurred, the former exceeded 410 K. With gear pairs Z (galvanizing) and M (MoS₂ coating) the variation in the bulk-temperature was similar to Fig. 2 until a destructive scoring failure occurred.

As an example, for the case of gear pair M, photographs of the scored tooth surfaces of the pinion and the wheel when the bulk-temperature slightly dropped and

Fig.2 Variation in bulk-temperature of wheel

Fig.3 Photographs of scored tooth surface of gear pair M

when a destructive scoring failure occurred are shown in Fig. 3.

Figure 3 (a) is photographs when the test machine was immediately stopped just after the bulk-temperature reached a peak. At the center of the tooth face of the pinion, relatively small scratched scars were observed in the sliding direction. Thus, it seems that when the bulk-temperature reached the peak, the degree of a surface failure by scoring was slight, and the surface failure was restricted to one part of the working tooth faces (primary scoring). Further, the initial scoring failure extended all over the tooth faces as the gears were run, and the bulk-temperature dropped because the smoothness of the meshing faces of the gears transiently increased.

On the other hand, as shown in Fig. 3 (b), when a destructive scoring failure occurred, the MoS_2 layer was completely torn out and a significant failure of the base metals of the pinion and the wheel was also recognized. In the case of the pinion, as the frictional force acts in the direction of the tip and the root from the pitch point, the surface layer of the gear tooth flows in the direction of the tip and the root. Consequently, deep cracks were observed along the tooth trace in the vicinity of the pitch point. In addition, the conditions of the tooth faces in the other gear pairs were similar to those in gear pair M.

3.2 Life of gears up to a scoring

With respective gear pairs, the time and the transmitted works per unit face

Fig.4 Life of gears to occurrence of destructive scoring failure

width until a destructive scoring failure occurs are shown in Fig.4 as a function of the thermal conductivity of the surface layer of the gears, where the ordinate indicates the running time and the transmitted works after the oil supply was stopped (after the start of the tests under dry friction).

The life of the gears to the occurrence of a destructive scoring failure under dry friction is longer in the order of gear pairs C, G, Z, M, P and U. In addition, the order of the time until an initial scoring failure occurred also agreed with that until a destructive scoring failure occurred. When the life up to the occurrence of a destructive scoring failure under dry friction was compared with the scoring resistance under forced lubrication shown in the previous report, it was recognized that the life of gear pair G (graphite coating) considerably increased and that, on the contrary, the life of gear pair M significantly decreased.

From these test results, it can be considered that the heat quantity generated per unit time on the meshing faces by a frictional force under dry friction was larger than that under forced lubrication because the oil film could not be formed on the meshing faces under dry friction. Therefore, the life of the gears under dry friction can be considered to be affected by the thermal properties (the diffusibility of the frictional heat) of the coatings unlike the lubricity.

3.3 Gear noise and acceleration due to oscillation of gear box

In the case of gear pair P, the variations in the power spectrum of the sound pressure level (C-characteristics) of the gears and the strain at the compression side of the tooth fillet of the wheel are shown in Fig.5. In this figure, the number of the stages from (1) to (5) corresponds to that of the stages at which the variation in the bulk-temperature of the wheel occurred; stage (1) indicates a time point when a lubricating oil supplied, stage (2) indicates a time point just after the oil supply was stopped, stage (3) indicates a time point when the bulk-temperature

reached a peak, stage (4) indicates a time point when the bulk-temperature slightly dropped, and stage (5) indicates a time point just before the test machine was stopped. The static strain at the tooth fillet is that before the running of the gears.

From this figure it can be seen that the sound pressure level of the gears between stages (1) and (3) approximately consists of the mesh frequency f_z (1397 Hz) and the harmonic ones $2f_z$, $3f_z$ and $4f_z$ and that, particularly, the sound pressure level at the 1st mesh frequency is significantly large. At stages (4) and (5), however, a considerable increase in the sound pressure level at the frequency different from the mesh frequencies $f_z \sim 4f_z$ is recognized. Particularly, the value of the

sound pressure level (at all pass frequencies) at stage (5) was about 4 dB larger than that at stage (1). In this case, the occurrence of a destructive scoring failure was detected by the variation in the power spectrum of the sound pressure level.

With respect to the dynamic strain at the tooth fillet, the wave of the dynamic strain at stages (1) and (2) is very different from that between stages (3) and (5), particularly, in the vicinity of the meshing point where the single tooth contact starts. Therefore, as evident also from the above photographs, it can be considered that the tooth profile is considerably transformed at stage (3) when an initial scoring failure occurs. Further, the maximum value of the strain at the tooth fillet increased with the progress of the stage.

Figure 6 shows the variation in the gear noise (sound pressure level at all pass frequencies) for respective gear pairs. In addition, Fig.7 shows the variation in the acceleration (at all pass frequencies) due to oscillation of the test gear box. In these figures, the tests were carried out under dry friction from 10 min after the start of the running. The time for the respective plotted points corresponds to that for the above mentioned stages between (1) and (5).

Variation in bulk-temperature of wheel

Fig.5 Variation in power spectrum of sound pressure level of gears and strain at compression side of tooth fillet of wheel

Fig. 6 Variation in sound pressure level

From this figure it is clear that the sound pressure level and the acceleration due to oscillation increased with elapse of time. Particularly, those for gear pairs C and G of which the life to a scoring was significantly long were also large at the stage when a destructive scoring failure occurred. When the bulk-temperature of the wheel transiently dropped (at the fourth plotted point), any decrease in the sound pressure level and the acceleration due to oscillation could not be recognized. Therefore, it can be considered that a scoring failure progresses at the stage.

As can be seen from the above results, the occurrence and progress of a scoring failure can be detected by the measurements of the sound pressure level, etc.

4. Conclusions

From the scoring tests under dry friction of spur gears with various coatings, the following results were obtained:

(1) The life of the gears to the occurrence of a destructive scoring failure under dry friction is longer in the order of gear pairs C, G, Z, M, P and U. There-

Fig. 7 Variation in acceleration due to oscillation of test gear box

fore, as for the effect of the coatings on the life of the gears under dry friction, it can be considered that the thermal properties of the coatings are more effective than their lubricity.

(2) The bulk-temperature of the wheel considerably rose just after the oil supply was stopped, and then its value reached a peak. After that, although the bulk-temperature slightly dropped, it rapidly rose again. Finally, a destructive scoring failure occurred, and then the gears could not run. As for the behavior of the bulk-temperature drop, it can be considered that the smoothness of the meshing faces of the gears transiently increases.

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