Friction and Wear Characteristics of Gears in High Vacuum*

Satoshi ODA**, Takao KOIDE**,
Minoru TANIGUCHI*** and Tokihiko TAKI****

This paper presents a study on the friction and wear characteristics of gears in high vacuum. A power-circulating-type gear testing machine with a vacuum chamber was developed, in which the coefficient of friction between the contacting tooth surfaces, and the temperatures of the gear tooth and the shaft can be measured simultaneously under various running conditions. The running tests for S 45 C, SUS 440 C and MoS₂-coated SUS 440 C gears were carried out in high vacuum and air environments by using the gear testing machine, and the coefficient of friction between the contacting tooth surfaces, the wear of the gear teeth, and temperature changes of the gear teeth, the shaft, etc. were measured. On the basis of these results, the friction and wear characteristics of gears in high vacuum were determined.

Key Words: Gear, Vacuum, Tribology, Friction, Wear, Solid Film Lubrication, Temperature

1. Introduction

Various kinds of gears are used in manipulators and robots, which are used in the development of the space stations, and in vacuum deposition equipment and surface analysis instruments, and these gears are often subjected to high vacuum environment. Therefore, it is necessary to determine the friction and wear characteristics of gears in high vacuum.

In the present paper, the friction and wear characteristics of gears in high vacuum were examined by carrying out the running tests for S 45 C, SUS 440 C and MoS₂ coated SUS 440 C gears in high vacuum and air environments using a power circulating type

gear testing machine designed for high vacuum environments, which was developed by the authors. Temperature changes of the gear teeth, the shaft, etc. were also measured under running conditions, and the generated heat and the heat flow in vacuum and air environments were investigated. Furthermore, for SUS 440 C and MoS₂-coated SUS 440 C gears, the friction and wear characteristics under the reference Hertz stress (maximum Hertz stress $\sigma_H = 735$ MPa) of the gears used in the Space Station Japanese Experiment Module (JEM) were also examined.

2. Experimental Method and Apparatus

2.1 Test gears

Dimensions of test gears used in this experiment are shown in Table 1. Test gears were of (a) normalized S 45 C, (b) SUS 440 C and (c) SUS 440 C coated with solid film lubricant (MoS₂) (thickness of solid film: 10 μ m). Table 2 shows the heat treatment and working conditions of test gears. Maximum surface roughnesses of S 45 C, SUS 440 C and MoS₂-coated SUS 440 C gears were $R_{\max} = 15, 5$ and 5 μ m, respectively.

* Received 13th March, 1995. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 60, No. 575, C (1994), pp. 2422-2428. (Received 22nd December, 1993)

** Faculty of Engineering, Tottori University, 4-101 Minami, Koyama-cho, Tottori 680, Japan

*** Tottori Sanyo Electric Co., Ltd., 7-101 Tachikawa-cho, Tottori 680, Japan

**** Faculty of Engineering, Okayama University of Science, 1-1 Ridai-cho, Okayama 700, Japan

2.2 Gear testing machine for high vacuum environment

Figure 1 shows the power-circulating-type gear testing machine designed for high vacuum environments, which was developed by the authors. The maximum applied torque is $T_{\max}=150$ Nm and the rotational speed n of the pinion can be varied continuously in the range of $n=30\sim 4\,500$ rpm. Magnetic seal units are used as the bearings of the vacuum chamber. The air in the chamber is exhausted by an oil diffusion pump. Figure 2 shows the load cell for frictional force between meshing tooth surfaces. The load cell is attached to the vacuum chamber, and the frictional force is detected with strain gages pasted to the load cell.

Table 1 Dimensions of test gears

		Test gear pair	
		Pinion	Gear
Tooth profile		Standard	
Module	m	4	
Cutter pressure angle	α_0	20°	
Number of teeth	z	18	19
Reference diameter	d_a	72 mm	76 mm
Whole depth	h	9 mm	
Face width	b	10 mm	
Center distance	a	74.5 mm	
Backlash	c_a	0.37 mm	
Operating pressure angle	α_s	21.03°	

Table 2 Heat treatment and working conditions of test gears

Material	S45C	SUS440C
Heat treatment conditions	$850^\circ\text{C} \times 1\text{h WQ}$ $620^\circ\text{C} \times 2\text{h AC}$	$1045^\circ\text{C} \times 1\text{h N}_2\text{Q}$ $170^\circ\text{C} \times 2\text{h AC}$
Hardness	Hv260	Hv660
Finishing method	Hobbed	Ground

2.3 Testing method

Running tests for gear pairs shown in Table 1 were carried out in air and high vacuum environments (degree of vacuum: $p=10^{-3}$ Pa). Test gears except for SUS 440 C (MoS_2) gears were unlubricated. Frictional force between meshing tooth surfaces, efficiencies, amounts of wear (wear weight and wear depth) and temperatures of the gear teeth, shaft and various positions in the vacuum chamber were measured. Coefficients of friction were obtained from frictional forces measured using the above-mentioned load cell, and efficiencies were obtained from the torque values of pinion and gear shafts. Wear weights were obtained from gear weight changes at various stages of the running test, and wear depths were obtained from pinion tooth trace profiles. Temperatures were measured using thermocouples attached to the gear tooth, shaft and various positions in the vacuum chamber (Fig. 3). The temperature of the tooth was measured at the point 4 mm away from the tooth tip on the center line of the tooth.

3. Experimental Results and Discussions

3.1 Coefficient of friction

Figure 4 shows the measured results of maximum

Fig. 2 Load cell for frictional force

Fig. 1 Power-circulating-type gear testing machine for vacuum environment

Fig. 3 Positions of thermocouples in vacuum chamber

Fig. 4 Coefficient of friction

coefficients of friction in the range of single tooth pair contact. In this figure, σ_H indicates the Hertz stress at the pitch point. $\sigma_H = 735$ MPa is the JEM reference Hertz stress. It is found from Fig. 4 that the coefficients of friction in vacuum are larger in the case of S 45 C gears and smaller in the case of SUS 440 C gears than those in air. It is known that the oxide film is formed on metal surfaces in O_2 atmosphere and this affects the coefficient of friction⁽¹⁾. In the case of S 45 C gears, the oxide film formed on the tooth surfaces prevents the adhesion of metals in air, but in vacuum ($p = 10^{-3}$ Pa) the oxide film is removed easily

Fig. 5 Efficiency

at the initial stage of the running test and much time is required for the oxide film to be formed. Therefore, the coefficients of friction of S 45 C gears in vacuum are larger than those in air. In the case of SUS 440 C gears, the oxide films were observed on the tooth surfaces both in vacuum and in air. These films are considered to be Fe_3O_4 or FeO in vacuum and Fe_2O_3 in air as determined by their colors (black in vacuum and brown in air). Since the Fe_3O_4 and FeO are softer than Fe_2O_3 ⁽¹⁾, the coefficients of friction of SUS 440 C gears in vacuum are smaller than those in air. The difference between the coefficients of friction of SUS 440 C (MoS_2) gears in vacuum and in air is small and the coefficients of friction are considerably smaller than those of SUS 440 C gear. It might be considered from these facts that the effect of MoS_2 solid film lubricant on the friction characteristics is fairly large and the coefficient of friction becomes considerably smaller by coating tooth surfaces with MoS_2 films. The coefficients of friction of S 45 C gears both in vacuum and in air are larger than those of SUS 440 C and SUS 440 C (MoS_2) gears.

3.2 Efficiency

Figure 5 shows the measured results of power transmitting efficiencies. The efficiency of each test gear is almost constant irrespective of the pinion speed within the range of $n = 30 \sim 150$ rpm and Hertz stress within the range of $\sigma_H = 147 \sim 392$ MPa. The efficiencies of S 45 C gear in vacuum are smaller than those in air. For SUS 440 C and SUS 440 C (MoS_2) gears, the differences between efficiencies in vacuum and in air are small. The efficiencies of SUS 440 C (MoS_2), SUS 440 C and S 45 C gears become smaller in the order mentioned both in vacuum and in air.

3.3 Amount of wear

Figure 6 shows the relationship between number of load cycles and wear weight w . The wear weights of SUS 440 C and S 45 C gears in vacuum are smaller than those in air. This might be because the wear particles adhere easily to the surface of each tooth since the contamination of the surface becomes smaller in higher vacuum⁽²⁾. The wear weights of SUS440C

Fig. 6 Wear weight

(MoS₂) gear in vacuum are slightly larger than those in air, and the rates of increase of wear weight with N in vacuum and in air are almost equal. For the JEM reference Hertz stress $\sigma_H = 735$ MPa, the scoring of SUS 440 C gear occurs just after the beginning of operation ($N = 1 \times 10^3$) and the wear weight increases rapidly, while the scoring of SUS 440 C (MoS₂) gear does not occur until $N = 9 \times 10^3$. Therefore, when the transmitted load is small, the selection of gear materials is not a serious problem, but when the transmitted load becomes large, it is necessary to coat the tooth surfaces with solid film lubricants since the scoring occurs easily and abruptly. The wear depth of each gear shows almost the same tendency as the wear weight.

Figures 7(a) and (b) show the profiles of gear teeth in the face width and tooth height directions of SUS 440 C (MoS₂) gear for $\sigma_H = 735$ MPa and $n = 100$ rpm in vacuum. It is found from Fig. 7 that the wear depth increases with N and that the wear progresses uniformly along the tooth profile and does not always become larger at the tooth tip and root, where the specific sliding becomes larger (Fig. 8). This might be because the wear in the vicinity of the pitch point where the specific sliding is zero progresses as a result of the peeling of films since the MoS₂ is of a laminated structure. Figure 9 shows the relations between N and wear weight w , wear depth h and coefficient of friction μ of the SUS 440 C (MoS₂) gear under the same running conditions as in Fig. 7. The wear weight and wear depth increase and the coefficient of friction decreases with increasing N for $N \leq 3 \times 10^3$, but these values become almost constant for $N = 3 \sim 6 \times 10^3$ and increase rapidly with N for $N \geq 6 \times 10^3$.

(a) Face width direction

(b) Tooth height direction

Fig. 7 Profiles of test gear teeth in face width and tooth height directions
[SUS 440 C (MoS₂) gear, in air, $\sigma_H = 735$ MPa, $n = 100$ rpm]

Fig. 8 Specific sliding

3.4 Tooth profile change

Figure 10 shows the tooth profile changes of test gears. The tooth profile changes of S 45 C gears with

N are fairly large even for $\sigma_H = 196$ MPa. Those of SUS 440 C and SUS 440 C (MoS₂) gears were fairly small for $\sigma_H = 196$ MPa. For $\sigma_H = 735$ MPa, the tooth

Fig. 9 Relationship between number of load cycles and amount of wear, wear depth and coefficient of friction
[SUS 440 C (MoS₂) gear, in vacuum, $\sigma_H = 735$ MPa, $n = 100$ rpm]

profiles of SUS 440 C and SUS 440 C (MoS₂) gears change with increasing N in the vicinity of the pitch point, and the degree of change of SUS 440 C (MoS₂) gear is considerably smaller than that of SUS 440 C gear. Thus the tooth profile change with N becomes considerably smaller even for large Hertz stress by coating the tooth surfaces with MoS₂ films.

3.5 Surface roughness

Figure 11 shows the surface roughness curves of test gears. The change in maximum roughness $R_{\max}$ of S 45 C gears in vacuum for $\sigma_H = 196$ MPa with N is small, but the $R_{\max}$ value in air tends to decrease with increasing N . This might be because the wear particles adhere easily to the surface of each tooth in vacuum as mentioned in Sec. 3.3, and have difficulty adhering in air and the surface asperities wear away with increasing N . The $R_{\max}$ values of SUS 440 C (MoS₂) gears decrease with increasing N both in vacuum and in air. This might be because the surface asperities of the MoS₂ films wear away with increasing N . The change in $R_{\max}$ values of SUS 440 C gears with N for $\sigma_H = 196$ MPa was fairly small both in

(a) S 45 C gear (in air, $\sigma_H = 196$ MPa, $n = 50$ rpm)

(b) S 45 C gear (in vacuum, $\sigma_H = 196$ MPa, $n = 50$ rpm)

(c) SUS 440 C gear (in vacuum, $\sigma_H = 735$ MPa, $n = 100$ rpm)

(d) SUS 440 C (MoS₂) gear (in vacuum, $\sigma_H = 735$ MPa, $n = 100$ rpm)

Fig. 10 Tooth profile changes

vacuum and in air. This might be due to the higher hardness (H_V 660), and smaller $R_{\max}$ ($R_{\max}=5\ \mu\text{m}$) of SUS 440 C gears. The $R_{\max}$ values of SUS 440 C and SUS 440 C (MoS_2) gears for the JEM reference Hertz

stress $\sigma_H=735\ \text{MPa}$ decrease with increasing N except in the vicinity of the pitch point of the SUS 440 C gear due to the effect of specific sliding on surface roughness.

3.6 Temperature

Figure 12 shows the temperature changes of the gear tooth, shaft and various positions in the vacuum chamber. In Fig. 12, a ~ d show the measuring positions of temperature and are the gear tooth, shaft, bearing cover and the position 60 mm away from the operating pitch point (see Fig. 3), respectively. Increments of temperature of a ~ c in vacuum are larger than those in air irrespective of N , but those of d in vacuum are smaller. This might be because the heat transfer, heat conduction and convection through gas

Fig. 11 Surface roughness

Fig. 12 Temperature changes of various positions in vacuum chamber (S 45 C gear, $\sigma_H=196\ \text{MPa}$, $n=50\ \text{rpm}$)

Fig. 13 Temperature changes of gear teeth

are not expected in a vacuum environment⁽³⁾. Figure 13 shows the temperature changes of gear teeth. Increments of temperature of teeth of S 45 C, SUS 440 C and SUS 440 C (MoS₂) gears become smaller in the order mentioned, and those in vacuum are larger than those in air.

4. Conclusions

The main results obtained from this investigation are summarized as follows.

(1) The coefficients of friction in vacuum are larger in the case of S 45 C gears and smaller in the case of SUS 440 C gears than those in air. The coefficients of friction of SUS 440 C gears are smaller than those of S 45 C gears both in vacuum and in air. The difference between the coefficients of friction of MoS₂-coated SUS 440 C gears in vacuum and in air is small and the coefficients of friction are considerably smaller than those of S 45 C and SUS 440 C gears both in vacuum and in air.

(2) The power transmitting efficiencies of S 45 C gear in vacuum are smaller than those in air. For SUS 440 C and SUS 440 C (MoS₂) gears, the differences between efficiencies in vacuum and in air are small. The efficiencies of SUS 440 C (MoS₂), SUS 440 C and S 45 C gears become smaller in the order mentioned both in vacuum and in air.

(3) The amounts of wear of S 45 C and SUS 440 C gears in vacuum are smaller than those in air, but those of SUS 440 C (MoS₂) gear in vacuum are slightly larger than those in air.

(4) The scoring of SUS 440 C gear occurs just

after the beginning of operation for the JEM reference Hertz stress $\sigma_H = 735$ MPa, while that of SUS 440 C (MoS₂) gear does not occur until the number of load cycles reaches $N = 9 \times 10^3$.

(5) The tooth profile changes of S 45 C gears with number of load cycles N are fairly large both in vacuum and in air, while those of SUS 440 C and SUS 440 C (MoS₂) gears are fairly small.

(6) The change in maximum roughness R_{max} of S 45 C gears in vacuum with number of load cycles N is small, but the R_{max} value in air tends to decrease with increasing N . The changes in R_{max} values of SUS 440 C gears with N are fairly small both in vacuum and in air, and the R_{max} values of SUS 440 C (MoS₂) gears decrease with increasing N .

(7) The wear of SUS 440 C (MoS₂) gears progresses uniformly along the tooth profile.

(8) Increments of temperature of gear teeth during operation in vacuum are larger than those in air, since the heat transfer, heat conduction and convection through gas are not expected in the vacuum environment.

Acknowledgement

The authors extend their sincere thanks to Dr. M. Nishimura of Hosei University and Mr. M. Kawamura of Kawamura Research Laboratories for their help in conducting this investigation. Mr. C. Namba of Tottori University was very helpful in carrying out the experiment and in discussing the experimental results. This research was partly supported by a scientific research fund from the Ministry of Education, for which the authors express their sincere gratitude.

References

- (1) Tanaka, K., Friction (in Japanese), (1985), p. 94, Nihon Kikaku Kyokai.
- (2) Nishimura, M., Vacuum and Tribology, Jour. Jpn. Soc. Mech. Eng., (in Japanese), Vol. 92, No. 848 (1989), p. 614.
- (3) Kawamura, M., Wear of Nuclear Reactor and Vacuum Machinery, Jour. of Jpn. Soc. of Tribologist, (in Japanese), Vol. 34, No. 5, (1989), p. 375.