

Study on the Prediction Technique of the Wear Amount of Polyoxymethylene

Masahiro Kada,¹ Masaru Ishikawa²

¹Technical Service Center, Polyplastics Co., Ltd., Fuji, Shizuoka, 416-8533 Japan

²Department of Polymer Science and Engineering, Faculty of Engineering, Yamagata University, Yonezawa, Yamagata, 992-8510 Japan

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ABSTRACT: The influence of the sliding velocity and atmospheric temperature on the specific wear amount of polyoxymethylene was evaluated with the ring-on-ring apparatus. The specific wear amount showed the variation of S-character type with maximum value, according to the change in the sliding velocity and the atmospheric temperature. When those results are plotted according to the sliding surface temperature, they have been found to be arranged as the same dependence. The specific wear amount of polyoxymethylene was assumed to be proportional to the

product of actual contact area and reciprocal of the fracture energy. Then, the temperature dependency of the product of the fracture energy, calculated from stress-strain curve, and the actual contact area, calculated from Hertz's equation with elastic modulus, was able to explain the sliding surface temperature dependency of the specific wear amount well. © 2006 Wiley Periodicals, Inc. *J Appl Polym Sci* 100: 4212–4218, 2006

Key words: polyoxymethylene; wear; strain; strength; modulus

INTRODUCTION

Polymers can be used in sliding pairs without lubrication. Among the semicrystalline polymers, polyoxymethylene exhibits good sliding properties. It is a basic requirement to predicate the wear amount for polymeric materials. There are a lot of recent resin wear researches performed, to understand the mechanism of the wear of polymer. They are as follows:

- Research of the relation between abrasion pattern, such as rubber, and wear property.^{1,2}
- Research to relate abrasive wear to friction coefficient and bulk physical properties, such as hardness, tensile strength, elongation, and strain at break.^{3,4}
- Research to relate adhesive wear to material viscoelasticity.⁵
- Research of relation between material transfer and wear.^{6,7}
- Research of relation between sliding surface temperature and wear.^{8–10}
- Research of the influence in wear test method and contact form on wear.¹¹

It has been suggested that the wear amount of material depends on the sliding surface temperature. Therefore, there are a lot of researches performed on the relation between the sliding surface temperature and the wear, which include metals.

Soda and Mori¹² researched the influence of sliding speed on the wear of iron against itself. It was suggested that the curve of the specific wear amount versus temperature varied alternately, with the increase of temperature. The iron oxide with a different oxidation index was generated because of the rise of temperature in the sliding surface, as the sliding speed was raised. Then, the mechanism of the change of wear amount was explained by solid lubrication effect, which is different from the oxidation index of iron oxide.

Watanabe and Yamaguchi⁸ researched the influence of both sliding velocity and load on the wear for PA6, high-density polyethylene and polyurethane. They showed that the effect of both sliding velocity and load on the wear can be normalized as the dependence of temperature of the wear on the sliding surface. There was a minimum value of the specific wear amount of PA6 in the sliding surface temperature 110–130°C. The elasticity modulus of PA decreases greatly at about 100°C, as the temperature is increased further beyond the glass transition point of about 45°C. Therefore, it was suggested that the slip at interface occurs easily, because the actual contact area rises remarkably and the substantial face pressure decreases. As the temperature is further increased at the sliding interface, the specific wear amount increased

Correspondence to: M. Kada (masahiro.kada@polyplastics.com).

again because of the wear powder as roll, which is generated at high temperature.

Tanaka⁹ researched the relationship between wear and sliding surface temperature. He showed that the thickness of the melt layer of resin on the interface accomplishes the key role.

Tajima¹⁰ researched the relationship between wear and sliding surface temperature. The specific wear amount of the polyoxymethylene has a maximum at 50°C of sliding surface temperature. It was showed from SEM micrographs of worn surface and polarizing microscope micrographs of the crystal form of worn surface of the polyoxymethylene that the abrasive wear occurs below 50°C, and the adhesive wear occurs above 50°C. Thus, there are a lot of researches performed on the relationship between the adhesive wear and the sliding surface temperature, and the relationship between the wear mechanism and physical properties was discussed in detail. On the other hand, the examination of relationship between the adhesive wear and the physical property is rarely because of the complexity of the phenomenon.

The purpose of this article is to examine the relationships between the bulk mechanical properties and adhesive wear over a wide range of temperatures, to construct the system of predication of the amount of wear.

EXPERIMENTAL

Material

Copolymerization polyoxymethylene (Duracon M90S made of Polyplastics Co. Ltd.) of molecular weight 68,200 and MFR 9 g/10 min was used for the wear-out evaluation.

Wear

The wear test was performed with a rotary friction and wear examination apparatus (EFM-3-E type made by Orientec Co., Ltd.), in accordance with the JIS K7218. The shape of the specimen is a midair cylinder type, in accordance with a method of JIS K7218. The size of the specimen is 25.6 mm in the outside diameter, 20.0 mm in the inside diameter, and 15 mm in length. The friction area is 200 mm². The wear test was performed by sliding the edge sides of these specimens mutually, as shown in Figure 1. It is a so-called ring-on-ring method. The specimens were made by injection molding under the condition of 200°C in barrel temperature and 80°C in mold temperature. The specific wear amounts were calculated by the expression as follows:

$$\begin{aligned} \text{Specific wear amount (mm}^3\text{/(N/km))} \\ = A/(B \times C \times D) \end{aligned}$$

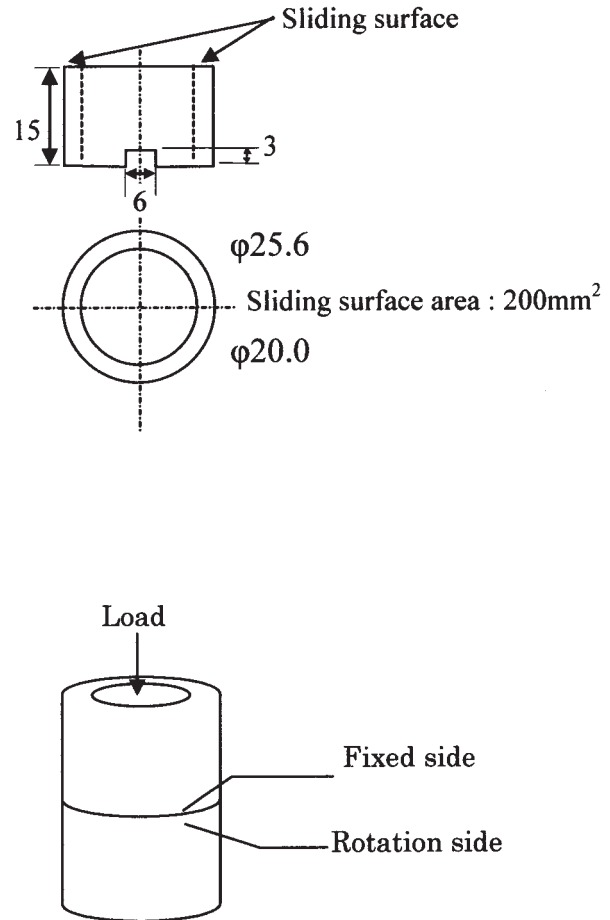


Figure 1 The dimension of the midair cylinder type specimen in accordance with A-method of JIS K7218 and disk-on-disk method.

where A is the wear loss (mg), B is the density (mg/mm³), C is the load (N), and D is the total sliding distance (km).

The running duration to measure the specific wear amount was decided from a preliminary experiment. The specific wear amount reached a steady state as the running duration passed over 3 h, as shown in Figure 2. Therefore, the running duration was decided to be 24 h, as a rule. In the condition with much wear, the running duration was properly shortened, as shown in Table I.

Measurement of temperature of the sliding surface

In general, the thermocouple and supersonic wave thermometer are enumerated to measure the temperature of sliding surface. It was already pointed out that the measured temperature in these methods is lower than the actual temperature of sliding surface because of the heat conduction or indirect measurement. Therefore, in this experiment, the sliding surface temperature was measured directly, to secure a suffi-

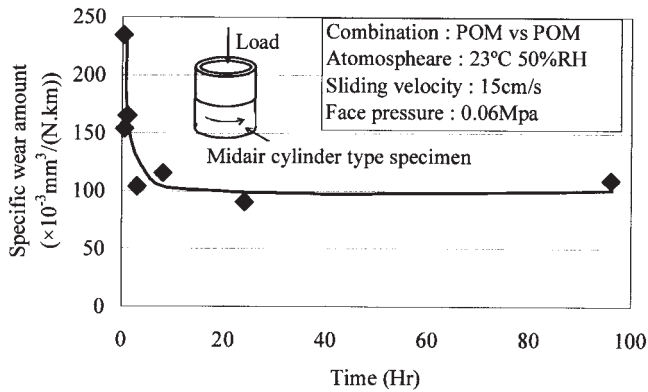


Figure 2 The specific wear amount of polyoxymethylene versus polyoxymethylene at each time (15 cm/s, 0.06 MPa, 23°C, 50% RH).

cient precision as follows. The cutting lack of 5 mm in width was installed on the sliding surface of a fixed side midair cylinder specimen, as shown in Figure 3. As a result, it enters the state always to be seen, with the surface of the rotation side specimen without the cutting lack. The laser beam of the radiation thermometer was irradiated to the sliding surface of the rotation side specimen through the cutting lack part, and the sliding surface temperature was measured. The time does not slide momentarily, once a rotation exists on the sliding surface of the rotation side specimen. However, it slid by more than 90% in one rotation, because the cutting lack width is only about 5 mm. Therefore, it seems that the difference between the estimated temperature by this method and the true temperature on the slid surface without the cutting lack is slight. The radiation thermometer is made of Tasco Japan Inc., THI-301S. The laser spot diameter φ was 1.2 mm. The specific wear amount was measured by use of the specimen without the cutting lack. Then, the temperature was measured separately with the

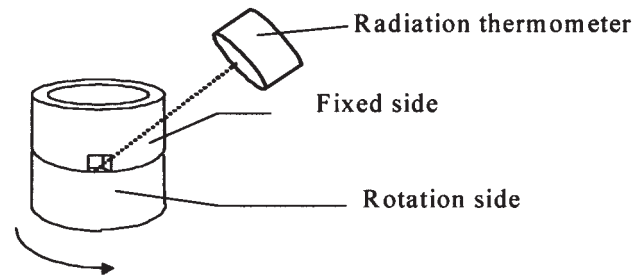


Figure 3 Measurement of sliding surface temperature.

cutting lack specimen. In each driving condition, the friction side temperature was steady enough after the passage of 15 min. Therefore, the sliding surface temperature was measured after 15 min.

Physical characteristic of friction material

The wear of the material is one of the fracture phenomenon. To investigate the relation between the wear behavior and the mechanical properties of the material, the tensile strength and the tensile strain at break were evaluated. The tensile strain at break at the high temperature is very large. Then, the measurement is difficult with a usual ISO dumbbell type test piece. Therefore, it was measured by the small tensile specimen (20 mm in gauge length, thickness 3.2 mm, and 3.2 mm in width). The specimen of TYPE S was used in accordance with ASTM D 1822M. The test was performed at 300 mm/s.

RESULTS

The variation of wear of polyoxymethylene with atmospheric temperature or sliding velocity

The effect of sliding velocity and the atmospheric temperature on the specific wear amount are shown in

TABLE I
Test Condition

Sliding velocity (cm/s)	Atmospheric temperature												
	-30°C	-10°C	10°C	23°C	40°C	50°C	60°C	80°C	90°C	100°C	110°C	120°C	130°C
5				*									
15	*	*	*	*			*	*	*	*	*	*	*
15.8				*									
30				*									
40				*									
50				*									
60				*(12 h)									
70				*(12 h)									
80				*(8 h)									
90				*(8 h)									

Face pressure: 0.06 MPa (Load: 11.77 N).

Running duration was 24 h as a rule. In the condition with much wear, the running duration was properly shortened.

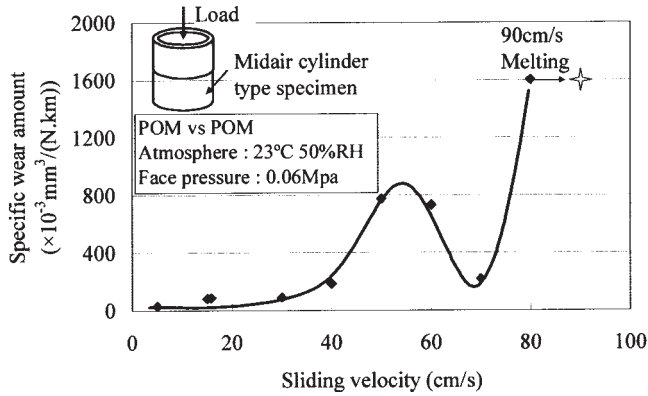


Figure 4 The specific wear amount dependency on sliding velocity.

Figures 4 and 5, respectively. The specific wear amount showed the total of a rotation side and a fixed side. The variation of the specific wear amount can be characterized by the curve of S-character type with maximum value, according to the change in the sliding velocity and the atmospheric temperature. As the sliding velocity increased at 23°C of atmospheric temperature, the specific wear amount increased gradually, and reached the extreme value at 50 or 60 cm/s. The specific wear amount decreased, as the sliding velocity increased further. When it approached a limit PV value, the specific wear amount increased again. It is found that the curve of the specific wear amount versus the sliding velocity has a peculiar tendency as like S-character. The change of specific wear amount with the atmospheric temperature is similar to that in the sliding velocity. At the 15 cm/s of sliding velocity, as the atmospheric temperature increased, the specific wear amount increased gradually, and reached the extreme value at about 90°C.

The variation of sliding surface temperature with the sliding velocity

Figure 6 shows the variation of the sliding surface temperature with the sliding velocity. The sliding sur-

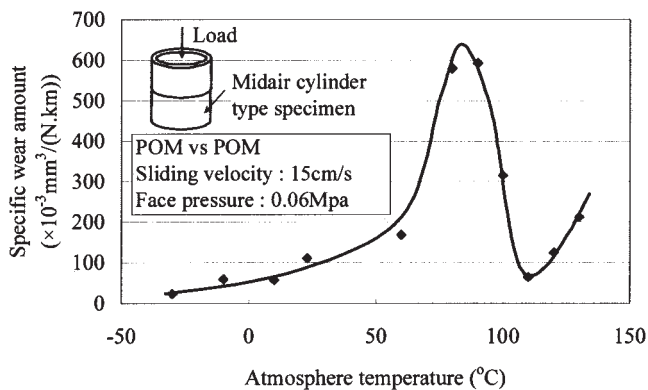


Figure 5 The specific wear amount dependency on atmospheric temperature.

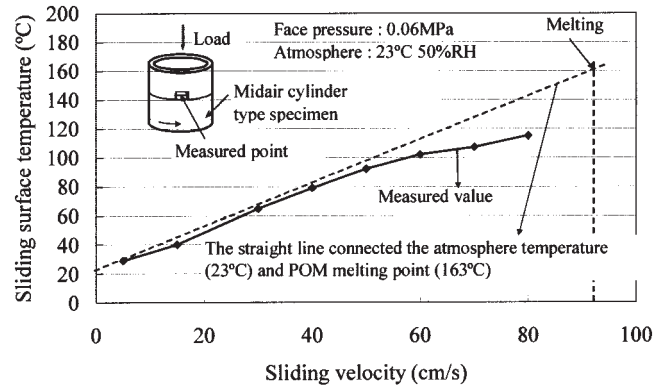


Figure 6 Sliding surface temperature of the polyoxymethylene versus polyoxymethylene at each sliding velocity.

face temperature increased linearly with the increase of the sliding velocity. It has already been pointed out that frictional heat generation is in proportion to “friction coefficient × face pressure × sliding velocity,” because it is equivalent to the work rate. In general, the variation of sliding surface temperature is complicated, because the friction coefficient of materials depends on the driving condition. It is considered that the linear relation between sliding surface temperature and sliding velocity is achieved, because the coefficient of dynamic friction does not change greatly in the combination of the same resin. The dotted line in Figure 6 is a straight line that connects the following two points. One is a point assumed to be 23°C, which is at room temperature. The other point at 90 cm/s, corresponding with limit PV, is a point assumed to be 163°C, which is the melting temperature of polyoxymethylene. The measured temperatures are slightly lower than this dotted line value, when the sliding velocity is low. The gap with this measurement value gradually expands with the increase of sliding speed. When the slipping speed is high, the temperature at the inside and outside of the edge of the sliding surface is much lower than the center of the sliding surface. It is guessed that because the radiation thermometer of spot diameter φ (1.2 mm) measures the average temperature, the low temperature is estimated. This speculation is confirmed by the rapid decrease of the temperature when the laser spot of the radiation thermometer moves from the center part to 0.2 or 0.3 mm outer or inner at the high sliding velocity. At low sliding velocity, such a phenomenon has been eased. Therefore, it is considered that a substantial, maximum temperature is a dotted line part of Figure 6.

It is known that the curves of wear amount versus the sliding velocity can be converted into the curve of wear amount versus sliding surface temperature by use of the relation between the sliding surface temperature and the sliding velocity. Figure 7 shows the converted curve in comparison with the curve of wear

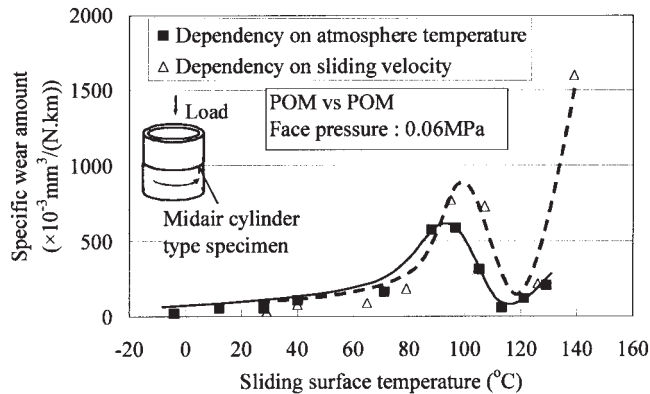


Figure 7 The specific wear amount dependency on atmospheric temperature.

amount as a function of atmosphere temperature. Those curves were almost in agreement, though the converted curve is shifted to the high sliding surface temperature in comparison with the atmosphere temperature dependency. That is, when the sliding surface temperature is the same, the tendency and the value of the specific wear amount are almost corresponding, regardless of the sliding velocity or the atmospheric temperature.

The fracture energy dependency on temperature

Because wear is one form of fracture, it is guessed that the wear of the polymeric material is closely related to the fracture mechanism. In general, under shearing deformation, a molecular chain of polymeric materials is oriented to the direction of maximum principal stress by the plastic deformation after yielding. The resistance to the plastic deformation increases by orientation hardening together with the formation of fibrils, when the plastic strain increases. The breakdown of fibril is caused by the molecular chain slipping or a molecular chain self-breaking. It seems profitable to evaluate the fracture due to shear deformation on wear by means of fracture energy. The fracture energy is a work until breaking. Therefore, the precise definition is the area of the stress-strain curve. The plastic strain of polyoxymethylene at break is large. Therefore handily here, "strength (σ) \times strain at break (ϵ)" is defined as the destruction energy in this study. The change of tensile strength and strain at break, according to an increase in the test temperature, are shown in Figure 8. The change of calculated fracture energy ($\sigma\epsilon$), according to the test temperature, is shown in Figure 9. The fracture energy increased rapidly as the temperature increases over 100°C, because of the increase of strain at break.

DISCUSSION

Figures 4 and 7 points out that the specific wear amount dependency on sliding velocity and atmo-

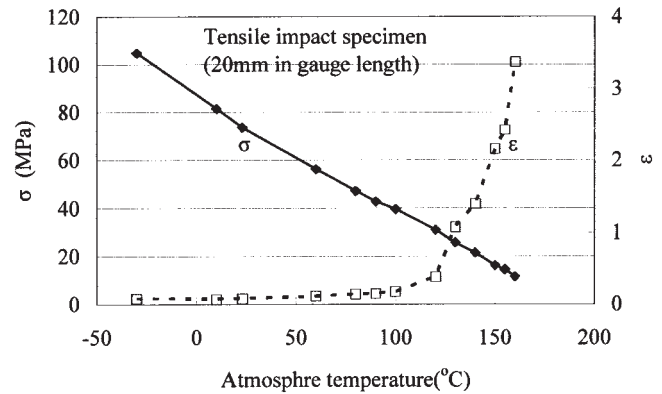


Figure 8 The temperature dependency of tensile strength (σ) and strain at break (ϵ).

spheric temperature can be arranged as same dependency, when they are plotted according to the sliding surface temperature.

The wear mechanism was guessed as follows: The polymer deforms plasticity by the shearing force due to the friction. The fibril with the oriented structure of the molecular chain is developed by the orientation hardening. The wear was caused by the break of fibril. According to this mechanism, the wear of polymer is depressed when the fracture energy until breaking is large. Figure 9 shows the variation of reciprocal of the fracture energy with the increase of temperature. $1/(\sigma\epsilon)$ decreases rapidly above the temperature of 100°C. This result shows that it becomes difficult to be worn above 100°C. Evidently, it is not corresponding to the result of the wear experiment.

The actual contact area on the sliding interface is smaller in comparison with the apparent contact area on the sliding surface, as shown in Figure 10. A lot of researchers explained friction and wear based on this idea.^{13,14} And, when the friction and wear is discussed, this idea is often quoted now. It seems that the actual contact area depends on the load, temperature,

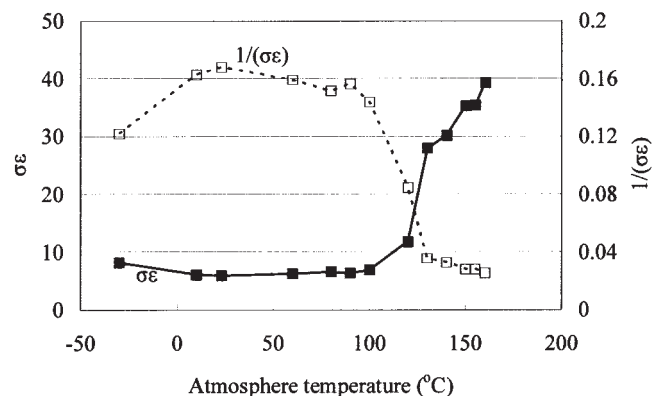


Figure 9 The temperature dependency of the fracture energy and the reciprocal of the fracture energy.

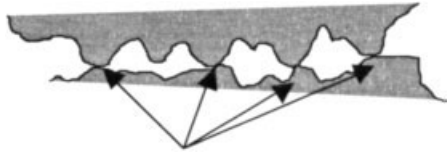


Figure 10 The expanding sketch of the sliding surface (The actual contact area).

and unevenness in the sliding surface. When the sliding surface temperature is high, the area contacted with each other on the sliding surface grows, because the elastic modulus of the resin decreases. Therefore, it is guessed that the wear increases by increasing the area to be broken (Fig. 11). To examine these dynamically, the model of the Hertz's contact was assumed as Figure 12. It was assumed that all projections were same-size hemisphere projections. This actual contact area is calculated from the Hertz's equation as follows:

$$\text{Actual contact area} = N\pi[3WR\{1 - \nu_1^2\}/E_1 + (1 - \nu_2^2)/E_2\}/8]^{2/3} \quad (1)$$

In this equation, N is the number of contact projections, π the circle ratio, R the radius of the hemisphere, ν the Poisson's ratio, E the elastic modulus, and W is the load. Because polyoxymethylene is combined with itself in this experiment, both materials can be considered to be the same elastic modulus and Poisson's ratio. Therefore, the equation is rewritten as follows:

$$\text{Actual contact area} = N\pi\{3WR(1 - \nu^2)/(4E)\}^{2/3} \quad (2)$$

The actual contact area at each temperature was calculated by substituting the polyoxymethylene elastic modulus¹⁵ for this expression. The actual contact area

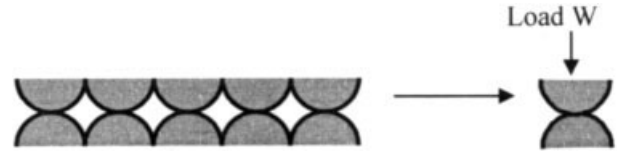


Figure 12 The model to calculate the actual contact area.

at 23°C was assumed to be 1 and the relative value at each temperature calculated, because it was difficult to calculate the absolute value of the actual contact area. The result is shown in Figure 13. It is guessed that the actual contact area grows with the increase of temperature. Therefore, if resistance to wear is the same, the rise of the temperature promotes the wear. It is guessed that wear is proportional to the reciprocal of the fracture energy, if the contact form is the same. Therefore, the specific wear amount of the material may be proportional to the product of the actual contact area and the reciprocal of the fracture energy. That is, it might be appropriate to assume the following equation:

$$\text{"Specific wear amount"} \propto \text{"actual contact area"} \times 1/(\sigma\varepsilon) \quad (3)$$

Figure 14 shows the variation of the relative presumption value of the specific wear amount with the surface temperature, which is calculated from Figures 8 and 13 based on the assumption.

Figure 15 shows the variation of specific wear amount with the sliding surface temperature and sliding velocity in comparison with that of the actual contact area $\times 1/(\sigma\varepsilon)$. The temperature at Figure 15 means the sliding surface temperature for the specific wear amount dependency on the sliding surface tem-

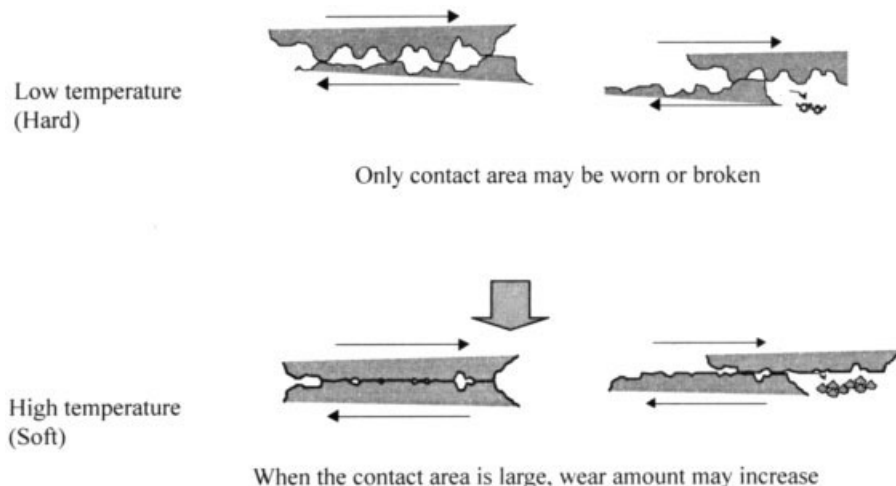


Figure 11 The relation between the wear and the actual contact area. (a) Low temperature (hard): only contact area may be worn or broken. (b) High temperature (soft): When the contact area is large, wear amount may increase.

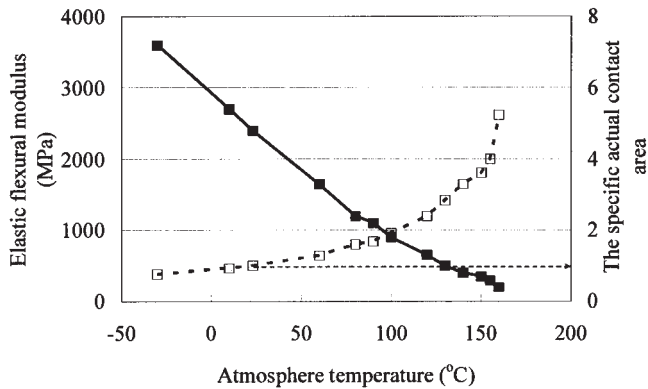


Figure 13 The temperature dependency of elastic modulus and the specific actual contact area.

perature and the atmosphere temperature, and means the atmosphere temperature for “the actual contact area $\times 1/(\sigma\varepsilon)$ ” dependency on atmosphere temperature. It is found that the variation of calculated specific wear amount from the fracture energy and the actual contact area, estimated with elastic modulus and sliding surface temperature, is in good agreement with the variation of measured specific wear amount with sliding velocity and the atmosphere temperature. This result shows that a dynamic base required predicting the amount of wear that could be clarified.

CONCLUSIONS

In this investigation, the influence of the sliding velocity and atmospheric temperature on specific wear amount of polyoxymethylene was evaluated with ring-on-ring apparatus. The specific wear amount

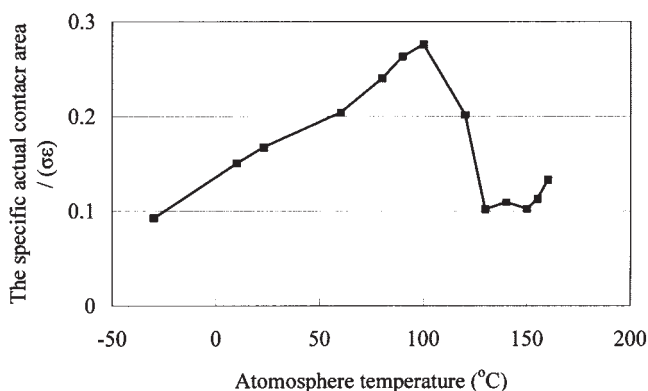


Figure 14 The temperature dependency of the specific actual contact area/ $\sigma\varepsilon$.

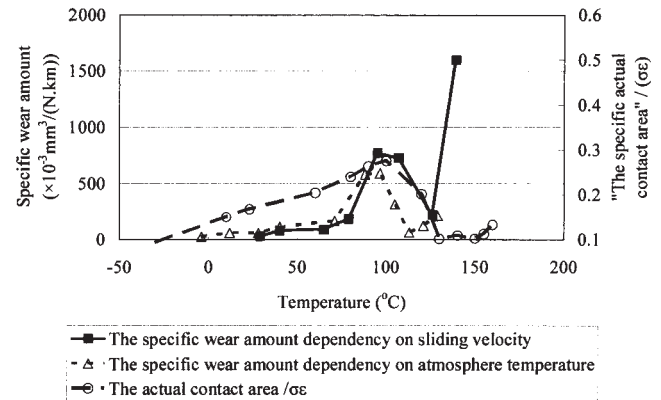


Figure 15 The arranged result of three dependency.

showed the dependence in S-character type with maximum value, according to the change in the sliding velocity and the atmospheric temperature. When those results are plotted according to the sliding surface temperature, they have been found to be arranged as the same dependence.

The specific wear amount of polyoxymethylene was assumed to be proportional to the product of actual contact area and reciprocal of the fracture energy. Then, the temperature dependency of product of the fracture energy, calculated from stress-strain curve and the actual contact area calculated from Hertz's equation with elastic modulus, was able to explain the sliding surface temperature dependency of the specific wear amount well. This result shows that a dynamic base required to predict the amount of wear that was to be clarified.

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