TRIBOLOGY SERIES, 16

TRIBOLOGY OF PLASTIC MATERIALS

YUKISABURO YAMAGUCHI

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Their Characteristics and Applications to Sliding Components

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PREFACE

Plastic materials excel in lightness, electric and heat insulation, corrosion resistance, absorption of impact and vibration, colourfulness and mouldability. They can be economically produced, and their properties are easily modified by forming composites or blending. Uses in various forms are thus widespread and range from toys and home appliances to industrial tools and machine elements.

In addition to the above-mentioned properties, it is worth noting that many plastic materials have excellent self-lubricating characteristics. Historically, phenolic resin was used for journal bearings and gears because of its ability to operate without conventional lubrication and its vibration-absorbing qualities. More recently, applications of some semi-crystalline plastic materials, especially polytetrafluoroethylene and polyacetal, have been greatly extended to include sliding machine parts, as a direct result of their self-lubricating capabilities.

The friction and wear characteristics of plastic materials have been studied for over 50 years, but generally accepted theories and definitive experimental data have yet to be established because of the proliferation of new materials and the complications of simulating appropriate practical conditions in the laboratory. Nevertheless, when these materials are intended to be used for sliding parts, workable theories and reliable experimental data are required.

During the past 25 years, the author's experiments on the sliding behaviour of plastic materials and their applications in machine elements have led to the accumulation of considerable experimental data and the formulation of practical theories. Most of the data presented in this book were obtained in a single laboratory. Therefore, if these data are to be used in practical situations, caution must be exercised and the conditions carefully analyzed.

This book is a translation, for the most part, of a book entitled *"Lubricity of Plastic Materials"*, which was published originally in Japanese by the Nikkan Kogyo Newspaper Co. after previously appearing as a series of articles in the journal *"Engineering Materials"* during the course of one year.

The book is divided into four parts. Chapters 1 and 2 deal with current theories of friction and wear, and include discussion of various hypotheses based upon experimental studies. Chapter 3 details experiments designed to improve tribological performance via polymer blending and composite production, whilst Chapter 4 explains how the data obtained from these experiments can be applied to sliding machine parts. It is the author's hope that the information may prove useful for the design of plastic materials and components and that it may be a stepping-stone toward future innovations in this field.

I would like to thank Dr. Y. Oyanagi, Mr. S. Amano, Mr. S. Sato, and especially Dr. I. Sekiguchi of the High Polymeric Material Laboratory at Kogakuin University, for their help and assistance throughout the course of this project. I am also grateful to the staff of Nikkan Kogyo Newspaper Co. for their constant support, to Dr. Y. Hazeyama for his help with the translation into English, to Dr. John Lancaster for his final editing of the text, and also to the Oiless Kogyo Co. for their financial assistance. I would also like to take this opportunity to thank Dr. John Lancaster and Dr. Brian Briscoe for being instrumental in arranging for this work to be published in English.

Y. Yamaguchi

FOREWORD

Recent years have seen the publication of several books in English on the subject of Tribology, and indeed the "Elsevier Tribology Series" has contributed significantly to this number. In the particular area of Polymer Tribology there have been two significant Soviet texts as well as at least one important dedicated conference publication. In addition, a recent compilation on "Composite Tribology" is largely devoted to polymeric systems. Many international conferences continue to devote sections to Polymer Tribology and a number of non-tribological texts have reviewed the subject in self-contained chapters. Compared with the situation perhaps twenty years ago, the subject of Polymer Tribology is thus now reasonably well furnished with general introductory material.

The present book naturally contributes directly to this information source, being one of four dedicated textbooks on the subject. The main structure of the book is laid out on classical lines and incorporates many ideas which have evolved in the Western literature. It should be borne in mind, however, that this book is very much a Japanese view of the important elements of the subject and, in detail, tends to concentrate on those topics in which the author and his group have made notable original contributions. In many ways, this is perhaps the main value of the text. The Western Tribologist has now, with this book and the Soviet ones, an overall international view of the way in which Polymer Tribology has developed as a subject. Perhaps the main surprise for these readers will be how similar the development of the subject has been in the three geographical areas. Clearly, this must reflect the many international contacts which occurred during the formative years of the subject. There are obviously differences in emphasis, style and approach, but the basic ingredients of fundamental principles coupled with a desire to develop a reasoned and confident predictive capacity is a common theme.

We, personally, were particularly pleased to be asked to provide the foreword to this text as we were fortunate enough to meet Professor Yamaguchi on a visit to Japan in 1985. At that time, we were able to visit his laboratories, gain a good appreciation of the wide range of his activities in polymer science and technology and also see the present book in the original, Japanese version. Our main overall recollection of that visit to Japan was the stimulating feeling engendered by the discovery that Polymer Tribology was such a strongly developed subject in that country. A similar conclusion could, of course, be drawn from a perusal of the published literature, but personal contacts are naturally more telling. Although

Professor Yamaguchi's book was just one element which contributed to this opinion, we felt then, and indeed also feel now, that this impression deserved a wide audience. Hence our encouragement to the author to undertake the translation of his book into English. The book has its own technical merit, but perhaps its lasting contribution will be to provide a view of the development of Polymer Tribology in Japan. Polymer Tribology has now a reasonably long history and as such deserves to be recorded.

B.J. Briscoe
J.K. Lancaster

CONTENTS

CHAPTER 1

FRICTION

1.1 SLIDING FRICTION; THEORY AND EXPERIMENT

1.1.1 *Theory of sliding friction*

The so-called "adhesion-shearing theory" was advocated originally by Bowden and Tabor [1,2] to account for sliding friction and, more recently, a theory based on surface energy has been presented by Lee [3]. In this book, a theory which is based on the "adhesion-shearing" mechanism is presented and frictional resistance is discussed as it is related to the shearing force required to break the interface of the contacting parts. As shown in Fig. 1.1 the true contact surface area A (= $\int_0^n a$) is far smaller than the apparent contact area A_o. Minute contact areas such as a_1, a_2 shown in Fig. 1.1 adhere to each other under a normal pressure p, and relative sliding motion between A and B is then possible only by destruction of the interface in shear. Accordingly, the frictional resistance F (the resistance to movement along the contact surface) is the sum of the shearing destructive force Fs and the resistance Fd to deform the contact part:

$$F = Fs + Fd \tag{1.1}$$

In reality, $F \simeq Fs$ since Fd is far smaller than Fs, and the following equation may thus be obtained:

$$F = A \cdot \tau \tag{1.2}$$

where A is the true contact area and τ is the shear strength of the contact material. The true contact area A is presented generally as follows:

$$A = kP^m \tag{1.3}$$

where P is the normal load, and k and m are constants, depending on the materials. The value of A may be obtained theoretically by using Hertz's elastic law [4] or Meyer's law [5] on hardness as follows:

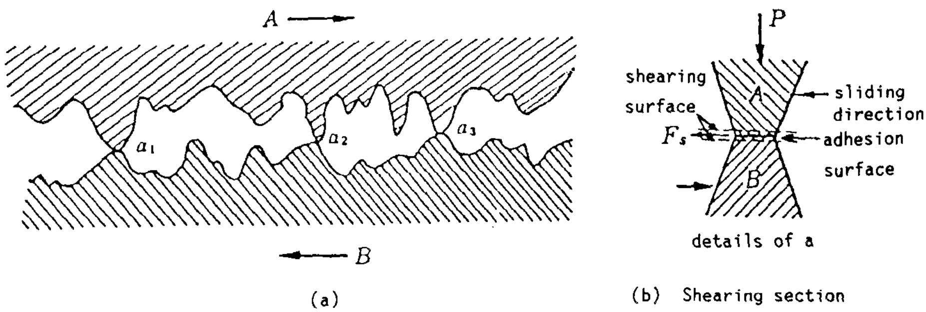

Fig. 1.1 Macroscopic section of sliding contact surfaces

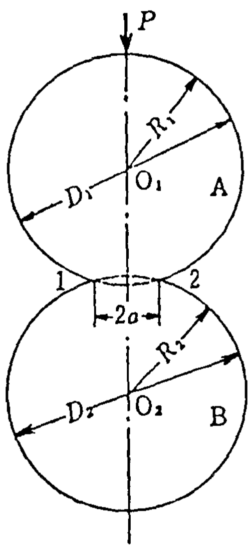

Fig. 1.2 Two spheres in direct contact

(i) *Theory based on Hertz's elastic law*

Two contact cases applying Hertz's law are discussed. One is for two opposing spheres and the other is for a sphere on a plane surface.

(1) *Two opposing spheres.* When two spheres with radii of R_1 and R_2 are in contact under a normal load P, as shown in Fig. 1.2, the radius a of the contact area predicted by Hertz's elastic law [4] is shown in the following equation:

$$a^3 = \frac{3}{4} \cdot \frac{R_1 \cdot R_2}{R_1+R_2} \cdot \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right) \cdot P \tag{1.4}$$

where ν_1 and ν_2 are Poisson's ratios and E_1 and E_2 are Young's moduli of spheres A and B, respectively. The contact area A is then

$$A = \pi a^2 = \pi\left\{\frac{3}{4} \cdot \frac{R_1 \cdot R_2}{R_1+R_2}\left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)\right\}^{2/3} \cdot P^{2/3} \tag{1.5}$$

For similar materials $E_1 = E_2 = E$, and of $\nu_1 = \nu_2 = 0.4$, then

$$A = 1.16\pi\left\{\frac{R_1R_2}{E(R_1+R_2)}\right\}^{2/3} \cdot P^{2/3} \text{ and} \tag{1.6}$$

$$\mu = \frac{F}{P} = \frac{A\tau}{P} = 1.16\pi\left\{\frac{R_1R_2}{E(R_1+R_2)}\right\}^{2/3} \cdot P^{-1/3} \cdot \tau \tag{1.7}$$

(2) *Sphere on a plane surface.* When a large sphere of radius R having smaller spherical asperities of radius r is in contact with a plane surface xx under a normal load P as shown in Fig. 1.3, the radius a of the circular contact area from Hertz [4] is given by:

$$a = K_1(PR)^{1/3} \tag{1.8}$$

where K_1 is a constant containing an elastic modulus and other constants. The maximum pressure P_o occurs at the centre and is

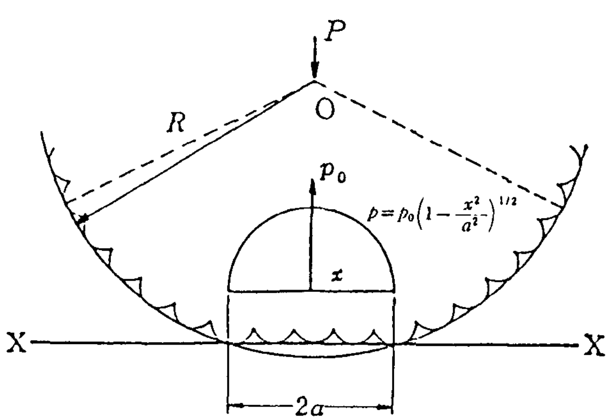

Fig. 1.3 Two surfaces, sphere and plane, in contact at many points

$$P_o = K_2 \cdot P^{1/3} \cdot R^{-2/3} \tag{1.9}$$

and the pressure p at any annulus of radius x is

$$p = p_o \left(1 - \frac{x^2}{a}\right)^{1/2} \tag{1.10}$$

If it is assumed that the asperities have equal radius x and are distributed uniformly as n/cm², the minute area dA of a circular ring with a breadth of dx at a radius x is $2\pi x \cdot dx$, and the load w supported by this area is

$$w = \frac{p}{n} \tag{1.11}$$

The area $\bar{a}$ of asperities is then

$$\bar{a} = K_3(w \cdot r)^{2/3} = K_3 \left(p \frac{r}{n}\right)^{2/3} \tag{1.12}$$

and the total true contact area A is

$$A = \int_0^a \cdot 2\pi n K_3 \left(\frac{r}{n}\right)^{2/3} \cdot p^{2/3} \cdot x \cdot dx$$

$$= \int_0^a K_4 r^{2/3} \cdot n^{1/3} \cdot p_o^{2/3} \left(1 - \frac{x^2}{a^2}\right)^{1/3} \cdot x \cdot dx$$

$$= K_5 \cdot r^{2/3} \cdot n^{1/3} \cdot R^{2/9} \cdot P^{8/9} \tag{1.13}$$

$$\mu = \frac{A\tau}{P} = K_5 \cdot r^{2/3} \cdot n^{1/3} \cdot R^{2/9} \cdot P^{-1/9} \cdot \tau \tag{1.14}$$

(ii) *Theory based on Meyer's law*

Pascoe and Tabor [6] have reduced equation (1.19) to find the true contact area and frictional coefficient by applying Meyer's law concerning indentation hardness. According to this, the relationship between the load P, diameter D of the indenter and diameter d of the indentation, as shown in Fig. 1.4, is:

$$P = ad^n \tag{1.15}$$

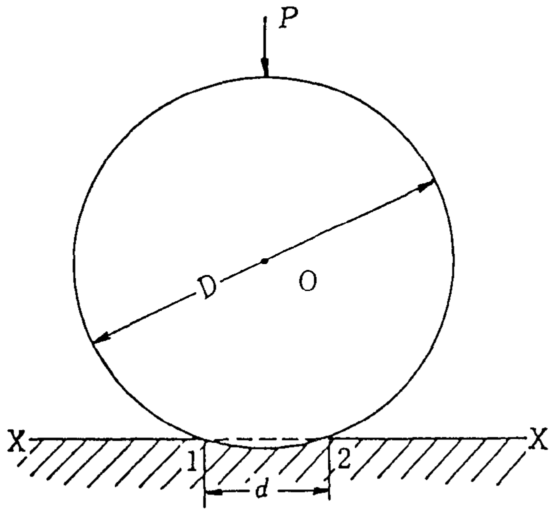

Fig. 1.4 Sphere and penetration of plane (Meyer's law)

$$K = a_1 \cdot D_1{}^{n-2} = a_2 \cdot D_2{}^{n-2} = a_3 \cdot D_3{}^{n-2} \ldots \tag{1.16}$$

From (1.15) and (1.16)

$$P = \frac{k}{D^{n-2}} \cdot d^n \tag{1.17}$$

and the true contact area A is

$$A = \frac{\pi}{4} d^2$$

$$= \frac{\pi}{4} \left(\frac{1}{K}\right)^{2/n} \cdot D^{2(n-2)/n} \cdot P^{2/n} \tag{1.18}$$

The coefficient of friction μ, presented similarly to equation (1.7) is therefore

$$\mu = \frac{A\tau}{P}$$

$$= \frac{\pi}{4} \cdot \tau \left(\frac{1}{K}\right)^{2/n} \cdot D^{2(n-2)/n} \cdot P^{(2/n-1)} \tag{1.19}$$

When the value of n in equation (1.19) is evaluated with respect to the value of m in equation (1.3), the following values of n are obtained: n is equal to 3 in equation (1.5) and is equal to 2.25 in equation (1.13). It is assumed that the value of n must be 3 when the material is perfectly elastic and 2 when the material is perfectly plastic. In other words, the value of A is proportional to P^m or $P^{2/3-1}$, and the value of μ is proportional to $P^{(m-1)}$ or $P^{-(1/3-0)}$.

1.1.2 *Experimentation based on sliding friction theories*

The relation where μ is proportional to $P^{(m-1)}$ has been previously explained by Shooter [7] and Lincoln [8], and has also been verified experimentally, to some extent, using Meyer's law by Pascoe and Tabor [6]. In this section, a discussion of two experimental cases is presented. One case is that of the contact of a steel sphere with a polymer plane applying Meyer's law and the other is that of contact between two polymer spheres applying Hertz's law.

(i) *Contact between a steel sphere and a polymer plane*

Using a Rockwell hardness tester, a steel sphere of diameter D was indented into a polymer or a steel plane under a load P, and the diameter d of the indentation was measured for each size of the sphere. The constants a and n in equation (1.15) and K in equation (1.16) were obtained and are presented in Table 1.1. Figure 1.5 shows the relationship between the load P and μ obtained from these constants and the shearing strength τ of various plastics from equation (1.19).

TABLE 1.1
Constants in Meyer's Law*

Material	a	n (mean)	K (mean)	μ (for Al)
Phenolics (PF)	6.9-38	2.76	54.8	0.37
Melamine Resin (MF)	9.5-35	2.67	49.1	0.30
PMMA	3.3-5.9	2.79	25.4	0.46
Polystyrene (PS)	4.5-4.8	2.75	23.5	0.36
Polycarbonate (PC)	2.3-5.9	2.75	19.8	0.56
Nylon 6	1.8-5.1	2.84	15.3	0.44
Steel	47-101	2.2	92.8	

*dia. of steel ball: 1/16-1/2", 20°C

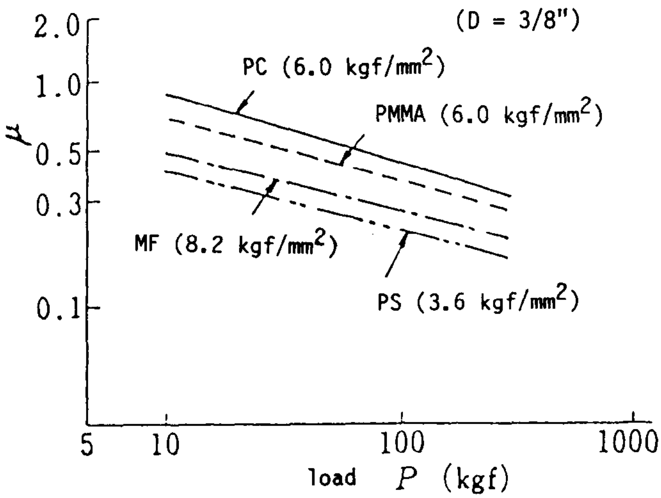

Fig. 1.5 Relationship between μ and P from Equation (1.19) for various polymers at different pressures, (____) slow the value of τ (20°C)

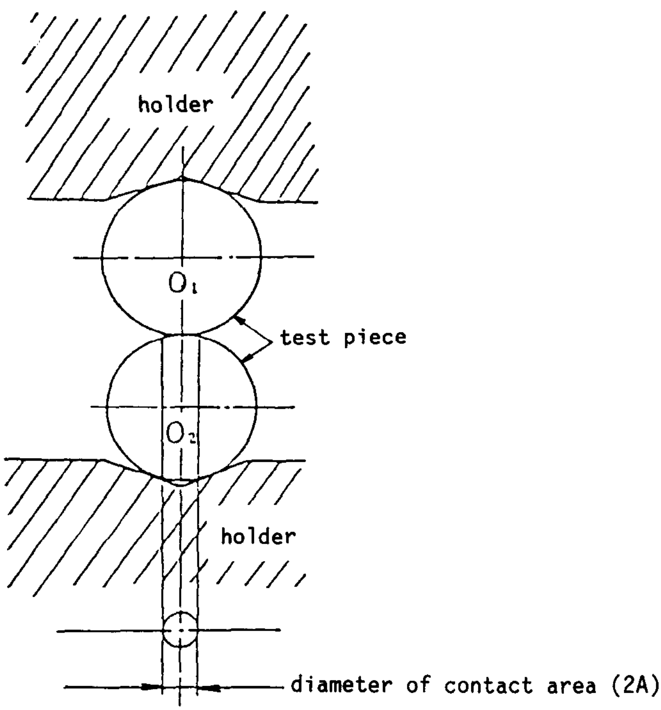

Fig. 1.6 Apparatus for measuring the contact area between two spheres