Mechanism of Friction and Real Contact Area

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Friction is a representative phenomenon of tribology caused by sliding motion and rolling motion. The function and operational performance of mechanical components are remarkably influenced by friction. The role of boundary lubrication is dominant in the operation of tribo-mechanical components since severe operating conditions can be allowed due to the improvement of processing accuracy in the surface finishing of mechanical components. Therefore, the clarification of the generation mechanism of friction with a relative motion in which a viscous effect is not included is important in analyzing the performance of mechanical components. It is the real contact area that becomes a starting point when the generation mechanism of the boundary friction is discussed. Therefore, more detailed discussion of the concept of real contact area is required. In this paper, we introduce mainly the content discussed in our research group regarding this subject.

Key Words*: friction, boundary friction, boundary lubrication, real contact area, adhesion*

1. "Friction" and its Position in "Tribology"

Tribology is defined as "the science and technology of interacting surfaces in relative motion and the practices related thereto." (The latter part is sometimes replaced by, "and of related subjects and practices.") This definition is interdisciplinary and abstract and shows a main feature of the academic field of tribology by inclusion of the two fields "science and "technology." The key words in this definition are "relative motion" and "surfaces." Relative motion refers to the macroscopic mode of motion between solid bodies opposing one other, specifically referring to sliding motion and rolling motion and is of great interest to the field of technology.

However, in order to study the nature of relative motion, it is necessary to examine it from microscopic viewpoint, particularly regarding the types of phenomena occurring on the contact area (i.e. the surfaces). Thus, these two key words are in a closely interactive relationship. Resolving the phenomena taking place on contact surfaces belongs to the world of science.

While friction is representative phenomena of tribology that accompanies such relative motions as sliding and rolling, the function of tribo-mechanical component relies on, and its performance is substantially dependent upon, the magnitude of friction and control of friction for its specific purpose. In fluid lubrication, a lubricating film formed by the fluid's viscous effect prevents solid-to-solid contact between relatively moving surfaces and thereby reduces friction. Here, friction predominantly depends on the viscosity of the fluid, and it is rare for matching between the material of the solid and the properties of lubricant fluid to be a significant problem. Therefore in the research field of tribology greater emphasis is placed on resolving the friction generation mechanism in the case of there being no viscous effect.

While the starting point for discussion over the mechanism of friction generation is the real contact area, i.e. the fundamental phenomena occurring on the contact surfaces, the real contact area appears to have already been discussed exhaustively, and lately this subject has not been put on the table very often. In this paper, therefore, we would like to present the subject of contact area centering around what was discussed within our research group to deepen our exploration of the mechanism of friction generation as information to readers. This is because we believe it is meaningful to reexamine contact area from the current point of view as the main factor of friction generation.

2. Exploration of Truth from Friction Phenomena Experienced in Everyday Life

We often experience in our everyday life phenomena demonstrating that a rougher surface produces greater friction and a smooth surface is likely to have less friction and be more slippery. The left-hand photo in **Fig. 1** shows rugged plates attached to a walkway surface making it unlikely for walkers to slip. This is mainly because the bottoms of the walker's shoes come into a state of matching with the rugged surface, which is fitted to the roughness theory regarding the friction generating mechanism between undulating surfaces. In contrast to this, the right-hand photo in **Fig. 1** shows a very slippery floor. However, if you walk with rubber-bottomed shoes even on such a floor, friction increases to such extent that a squeaking noise is produced. But even rubber shoes become quite slippery in case the floor is coated with water or oil. In my family, I am often asked to open tightly closed bottle caps. On such occasions, I usually can open the cap by moistening my hands to generate friction. However, if too much water is used, it makes my hand very slippery on the cap. Obviously this is because the fluid lubrication effect becomes dominant and prevents sufficient friction from being generated. A small quantity of water plays a critical role for increasing friction.

Rugged walkway surface　　Shiny floor surface

Fig. 1 Typical condition of road or floor surface

Incidentally, our laboratory once conducted an experiment concerning tribology that involved the walking of an ant. In this experiment, an ant was placed on a pad of specimen material. With the ant walking on the pad, the pad was gradually inclined until the ant slipped off the pad. The angle of inclination at this moment was used to determine the friction coefficient between the ant and the pad. For the specimen pad, five materials having different degrees of surface roughness were used. The results of the experiment, shown in **Fig. 2**, show that the friction coefficient varies significantly depending on the pad material. The acrylic resin pad had a friction coefficient three times as high as that of the aluminum pad. The influence of surface roughness was not notable in the low roughness range, but it became remarkable when the roughness exceeded 0.4 µm. The result of measurements comparing a living ant and a dead one is shown in **Fig. 3**. The surface roughness was kept as low as possible. In **Fig. 3**, it is clear that the influence of the pad material was significant with the living ant, but that in the case of a dead ant, the friction coefficient stayed within a range of 0.3 to 0.4 without being affected by the pad material. This value corresponds to the friction coefficient of many solid bodies under dry conditions. On the other hand, the living ant generally produced high friction coefficients such as 0.5 for aluminum and even over 1.0 for acrylic resin. This implies that a living ant secretes some substance from its legs that increases friction coefficient. Considering these results together with those in **Fig. 2**, we can conclude that friction coefficient in the case of a living ant is influenced by material and surface roughness. Thus, it was found that in cases such as when a small amount of moisture exists on the hand or contact is mediated by an ant's secretion, the friction coefficient was greater than in the case of dry friction. This kind of phenomena does not seem to have been discussed based on the conventional concept concerning boundary friction.

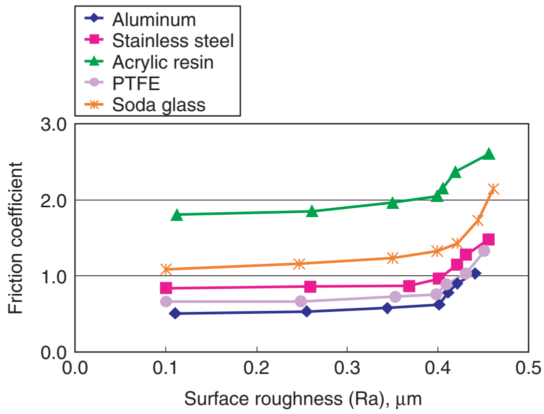


Fig. 2 Effects of material and surface roughness on coefficient of friction

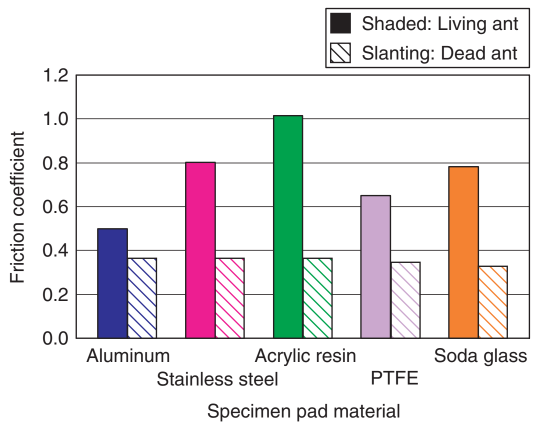
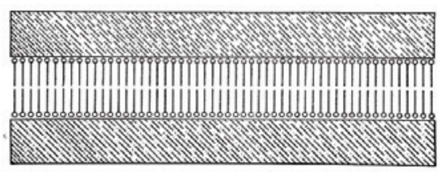


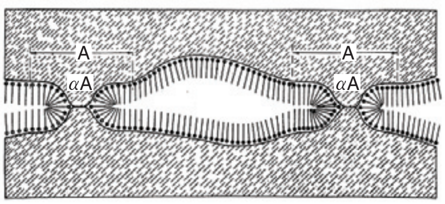
Fig. 3 Variation of friction coefficient depending on whether an ant is alive or dead

3. Attempt to Expand Boundary Friction Concept

The undulation of the surface of metal, a main material of mechanical elements, is not avoidable due to the nature of the surface processing methods. The undulation of sliding surfaces used in machines normally is several μm, although sometimes it may be around 0.1 μm when finished to maximum smoothness. If relatively sliding surfaces with a lubricant between them are subjected to successively severe sliding conditions, interference between the relatively moving surfaces eventually cannot be ignored. However, in some cases a good lubricating condition is maintained to the formation of oil film as thin as a molecular film. This is called boundary lubrication, and it has come to be considered important as one of the two major modes of lubrication for mechanical elements along with fluid-related lubrication. The boundary lubrication depends to a great extent on the reaction mechanism of additives such as the oiliness improvers and extreme pressure agents mixed in various lubricants. It was Hardy who proposed the basic concept of the boundary lubrication. **Figure 4 (a)** shows a conceptual illustration of the absorption film based on Hardy's boundary lubrication. Bowden and Tabor established a present-day boundary lubrication concept incorporating the concept of real contact area that takes into consideration the microscopic configuration existing on the surface (**Fig. 4 (b)**)[1]. Boundary lubrication has recently come to be regarded as more important for a couple of reasons. First, advances in surface processing technology have improved by far the surface roughness of machine elements, reducing interference between microscopic protrusions. Also, due to the introduction of new additives and improvement of their performance, the molecular film has become able to maintain its load carrying capacity without being broken by the relative motion. This means we have now entered a new generation wherein rule of molecular film dominates tribology performance in more and more fields.



(a) Hardy's model of absorption film



(b) Bowden & Tabor's model of absorption film taking into account microscopic configuration

Fig. 4 Concept of boundary lubrication film

Incidentally, the friction force F under lubricating condition is expressed as follows:

$$F = A_r \{\alpha s_m + (1-\alpha) s_i\} \quad (1)$$

A_r : Real contact area

α : Ratio of metal-to-metal contact area due to breakage of lubricating film

s_m : Shear strength of metal at contact

s_i : Shear strength of lubricating film

Because boundary lubrication has come to be regarded as an important lubrication mode along with fluid-related lubrication, discussion has been focused on boundary lubrication's capability to protect sliding surfaces and its role in friction reduction. As far as insights from the above equation are concerned, attention has been paid to the possibility of reducing friction by reducing the metal-to-metal contact area (reduction of α) or by reducing the shear strength of the lubricating film. We consider, however, that an important challenge will be to control friction purposefully paying attention to the mutual relationship between the mediums between the solid bodies and the surface of solid body on the basis of the influencing factors in the equation. In this regard, the issue of whether the real contact area refers specifically to the area wherein true contact is occurring between the solid bodies or to the area including such portion separated by a film as thin as a few molecules has not been adequately discussed, and it will be an important item for future discussion. In equation (1), the latter interpretation was applied.

As an example related to the issue of friction controlled in accordance with the purpose of application, we present, in **Table 1** and **Fig. 5**[2], the results of a research that triggered study on the existence of additives that increase friction. **Figure 5** shows the mechanism of friction characteristics generated by the paper-based friction material and automatic transmission fluids (ATF) dominantly used in passenger cars. This experiment shows that good friction-sliding speed characteristics can be obtained by appropriate selection of additives. Specifically, the effect of the additives incorporated here is two-fold: One is the effect of FM (friction modifier) in the low range bearing factor on the horizontal axis, and the other is the effect of detergent dispersant in the relatively high range bearing factor. This means that these two effects can jointly realize a uniform and high friction coefficient over a wide range of sliding speeds. As shown in **Fig. 6**, the friction material is composed of an organic paper matrix in which phenol resin was impregnated. This friction material is porous (**Fig. 7**), making it difficult for a fluid lubrication film to form even under lubricated sliding conditions, and boundary lubrication

Table 1 Properties of test oil[2)]

Symbol	Test oil	Dynamic viscosity, mm^2/s		Density, g/cm^3	VI
		40℃	100℃	15℃	
Oil A	Paraffin-based oil	31.0	5.35	0.863	105
Oil B	Same as above	90.5	10.9	0.870	107
Oil C	Same as above	408	30.9	0.879	107
Oil D	Oil A + FM additive (1 wt %)	31.0	5.35	0.863	105
Oil E	Oil A + Detergent dispersant (5 wt %)	33.4	5.65	0.869	107
Oil F	Oil A + FM additive (1 wt %) + Detergent dispersant (5 wt %)	33.4	5.65	0.869	107

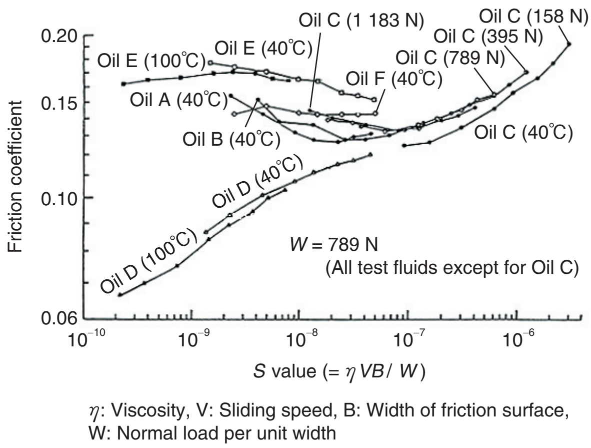


Fig. 5 Friction characteristics of paper-based friction material with various lubricants (Presentation by the Stribeck's curve)[2)]

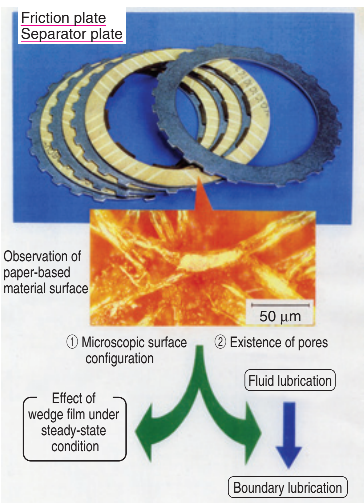


Fig. 6 Paper-based friction material

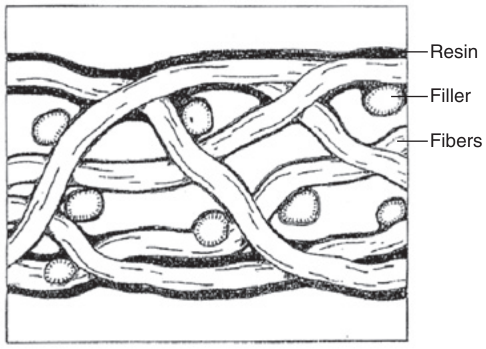


Fig. 7 Concept diagram of paper-based friction material

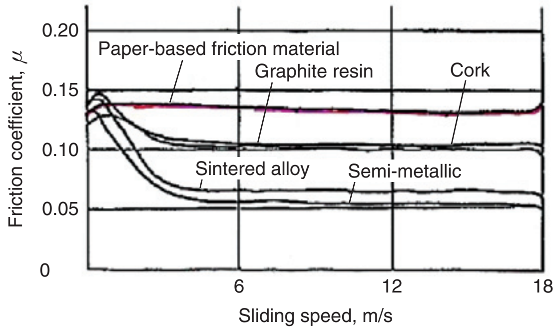


Fig. 8 Friction characteristics of various wet friction materials[3)]

has the characteristic of playing the main role on the contact surface. As shown in **Fig. 8**, satisfactory friction characteristics of the paper-based friction materials can be obtained from their combination with the automatic transmission fluid.

Friction characteristics of the paper-based friction material, when discussed in relation to the equation (1) , can be understood by imagining an expanded model of the conventional boundary lubrication concept with $\alpha = 0$ but with the friction effect becoming large due to a large S_i value. In other words, it is proposed that both mechanisms of decreasing friction and increasing friction can be discussed with boundary lubrication film.

4. Friction Generation Mechanism and Real Contact Area

In the field of tribology, surface-to-surface contact is divided into two concepts: apparent contact and real contact (**Fig. 9**). The former corresponds to the generally understood meaning of contact area. However, if two solid bodies with undulated surfaces are pressed against each other, contact does not take place over the entire area of apparent contact. The real contact area, i.e. the area on which actual contact is occurring, is derived, regardless of the apparent contact area, from the following equation (2) wherein P is the load by which the bodies are pressed against each other and p_m is the plastic flow pressure:

$$A_r = P/p_m \quad (2)$$

If the apparent contact area is geometrically defined, real contact area, except for its periphery, is considered to be studded with uniformly distributed portions, the sum of which equals A_r. An example of the ratio of the real contact area to the apparent contact area is shown in **Table 2**[4].

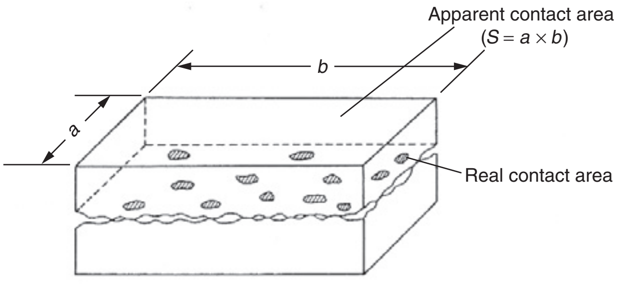


Fig. 9 Apparent contact area and real contact area

Table 2 Real contact area/apparent contact area under varying loads[4]

Load W (kgf)	A/S
300	1/130
100	1/700
20	1/10 000
3	1/170 000

A: Real contact area
S : Apparent contact area

This table shows how small the real contact area is in comparison to the apparent contact area.

In the atmospheric environment we experience on a daily basis, there exist oxygen molecules, water molecules, particulates, etc., and these exert a significant influence on friction. Therefore, the word "dry friction" can be considered to mean friction on surfaces made as clean as possible. Factors considered to be causes of dry friction generation are solid body surface adhesion, surface undulation meshing, ploughing such as in machining, hysteresis loss based on solid body viscoelasticity, resistance due to static electricity, etc. Coulomb and other early researchers believed that friction between clean surfaces of solid bodies was due to meshing of undulation on the surfaces.

If metal surfaces from which all film types have been removed are pressed against each other, the atoms of the metal will be in direct contact with each other. If the mating bodies are of identical metal, their contact portion will have strength not much different from the core of the metal. Such phenomena is referred to as adhesion and is considered, according to current prevailing theory, to be the main cause of friction generated on sliding surfaces in a machine. In reality, however, the above-mentioned various films are formed on the working surfaces, and the mutual binding forces in the contact area may be conceptually expressed as shown in **Fig. 10**. In the adhesion theory, the force required to shear the real contact portion, as expressed in the equation (2), is considered to be the friction force.

Supposing that the shear strength of the real contact area is s_i, the friction force F can be expressed in the following equations:

$$F = A_r \cdot s_i = P/p_m \cdot s_i \quad (3)$$

$$\mu = F/P = (P/p_m \cdot s_i)/P = s_i/p_m \quad (4)$$

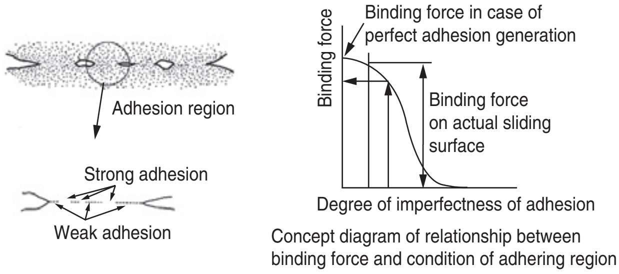


Fig. 10 Concept of binding forces in contact area

Since the surfaces of a solid body under dry friction are generally contaminated with absorption film and other contaminants, it is impossible to presume that the entire area of contact has a microstructure with the same binding strength as the core material. When two metal surfaces are placed in contact under a lubricated, loaded condition, just as much plastic flow as required to support the imposed load will be brought about, and thereby the real contact areas will be formed. Due to this deformation, the lubricant film is squeezed between the two metal surfaces and is subjected to high pressure, but because the pressure cannot be considered to be distributed evenly over the entire contact surface, it is possible that the lubricant film breaks in spots where the pressure is highest, resulting in true adhesion there. **Figures 4 (b)** and **10** show graphic representation of this situation. In this case, the resistance F against motion is expressed in equation (1), wherein A_r stands for the real contact area and α represents the ratio of area where the true adhesion is taking place due to breakage of the lubricant film. Since equation (1) is such that the term in { } substitutes s_i in equation (3), it may be regarded as an equation extending the adhesion theory to the boundary friction.

5. Laws of Friction and Review of Roughness Theory and Adhesion Theory as Friction Generation Mechanism

Amonton-Coulomb's laws concerning friction were proposed as experimental laws of friction in dry condition without lubricant. Nevertheless, since they also can be applied to cases that involve a lubricant film with a layer as thin as several molecules (a condition that belongs to boundary friction theory established in the 1920s), Coulomb's laws have been preferred cases that require quantitative investigation of phenomena concerning friction.

As far as friction between solid bodies under no lubrication is concerned, the law assumes that (1) friction is constant regardless of contact area, (2) friction is proportional to load, and (3) friction is constant regardless of sliding speed. Then, defining the friction coefficient as the value obtained by dividing the friction force by the normal force, the following are presented as basic laws: (1) The friction coefficient is constant regardless of contact area, (2) the friction coefficient is constant regardless of load magnitude, and (3) the friction coefficient is constant regardless of speed. Furthermore, the law (4) that dynamic friction is always smaller than the static friction is sometimes added. At that time, already two friction generation mechanism theories become discussed and compared, namely the roughness theory, which asserts that friction mainly attributes to meshing between minute undulations on the surfaces (including the process of one surface climbing up and down along the undulation of the other surface), and the adhesion theory, which asserts that intermolecular forces generated due to close approaching of the surfaces is responsible for friction. Two important propositions of Coulomb's laws were that the magnitude of friction increases in proportion to the load and that the magnitude of friction is constant regardless of contact area. If adhesion is the main cause, friction force is proportional to the contact area. Therefore, Amonton Coulomb denied the adhesion theory on the grounds that the magnitude of friction does not depend on the contact area. Instead, he adopted the roughness theory based on the concept that proportionality of friction magnitude to the load is due to the increase of potential energy for one surface to ride over protrusions on the other. What Amonton Coulomb and others meant by contact area was the apparent contact area, which has become our common knowledge today. Now it has become known that the real contact area involved in contact increases depending on the load and is constant under the same load, even if the apparent contact area changes. As a result, it has been clarified that the adhesion theory is useful to explain, without contradiction, the effect of contact area (apparent contact area) as well as the effect of loads.

Thus, as real contact area is important to quantitatively determining friction under dry or boundary lubricated conditions, various methods have been conventionally proposed (**Fig. 11**). Our research group has decided that the optical method can produce generally the most effective data and has made concentrated efforts to develop a system for measuring the real contact area under lubricated condition. **Figure 12** shows an example of such measurement results. By applying such measurement system to the sliding phenomena under the condition of boundary lubrication, we believe we will eventually be able to obtain data that are keys to the solution of the friction generation mechanism.

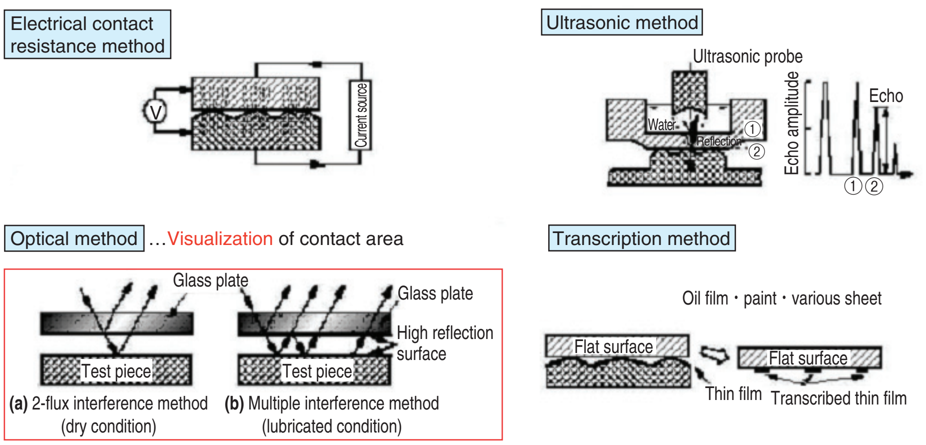


Fig. 11 Measuring method of real contact area

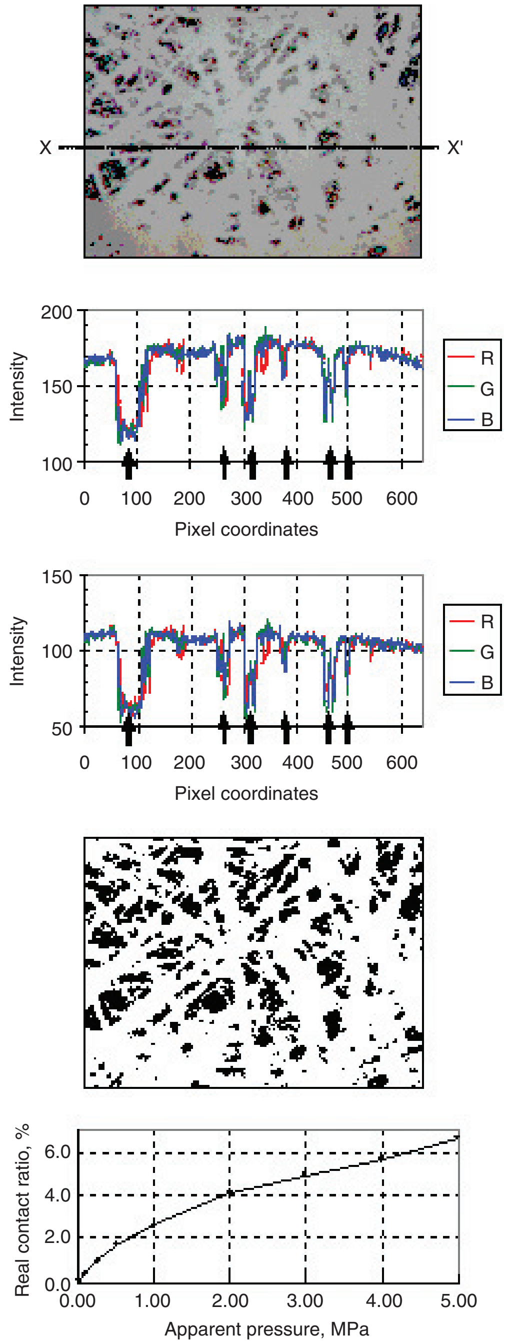


Fig. 12 Measurement example of real contact area by white light interferometory

6. Conclusion

There are many examples in showing that friction plays an important role in daily life and that it is influenced by surface undulation. However, in case of the relative movement of mechanical elements, the influence of friction based on the concept of adhesion is extremely significant. In these phenomena of adhesion, the concept of real contact area becomes significant when taking into account the actual microscopic configuration of the solid body surfaces. We will be happy if this paper helps readers understand these phenomena better.

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