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An Investigation of Air-leakage between Contact Surfaces*
(3rd Report, On Case in which Cast Iron and Brass were used as Specimen)

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In the last reports, assuming that the surface irregularities of specimens were isotropic and had a form of similar truncated cone whose deformations were elastic, plastic and elasto-plastic, the analytical solutions of equivalent gap for the fluid leakage between contact surfaces were verified with the experimental results using a lapped carbon steel. In this paper, the specimens, which are finished by lathing and grinding, are examined.

The results obtained can be summarized as follows:

(1) In the case in which the phenomenon of leakage was a radial and sector flow, the experimental values of equivalent gap obtained by assuming the surface roughness as anisotropic were in agreement with the analytical values with deviation about 8 %.

(2) The characteristic curves of parameters a and b for the carbon steel listed in the 2nd report can be applied for the materials tested in this experiment.

1. Introduction

The investigation of the machine elements having the mechanism of sealing, which can be obtained by pressing nominally flat metal surfaces against each other or by inserting a metallic gasket between them, becomes more important, when the problems of leakage between the tightened surfaces in the chemical or vacuum apparatus[1][2] etc. are discussed.

In the recent past, a number of workers have investigated the problems of flange sealing including gasket materials, e.g. Johnson[3], Lynch[4], Pearce[5] and Dukes et al.[6] using a thread joint.

The measurement of the deflection of a flange ring was described by Donald et al.[7], and Kollman[8], who studied the stress distribution in gasket. Bremner[9] studied the balance condition etc. for radial-face seals, while the measurements of the pressure in the fluid film and the static film-thickness profiles between seal faces were described by Billington[10] and Bupara et al.[11]

Assuming that the seal faces are rigid or elastic smooth surfaces, a successful achievement has been obtained by their efforts, and yet the actual phenomenon of fluid leakage between contact surfaces have not been perfectly clarified.

Regardless of the kind of metal used and the machining applied, there can be no doubt that the surface irregularities on metal surfaces are such that the analytical and experimental investigations of the mechanism of contact between metal surfaces, together with those of the behavior of supplied fluid between contact surfaces, are absolutely necessary for revealing the real mechanism of face seals.

In the above investigations, the geometrical shapes of surface irregularities were assumed by investigators to be a cone [12], a triangle [13][14], (i.e. the surface profile indicated by a surface roughness recorder), a pyramid[15], a semi-sphere[16] or a truncated cone[17]. The various forms which characterize the surface irregularities may be decided by considering the microscopic and statistical properties of surface roughness. For example, in the case of assuming the surface profile as a triangle, the deformations of surface irregularities can be derived from the slip-line field solutions given by Hill[18] providing that the material of the surface irregularities remains completely rigid until the yield criterion is satisfied and behaves as a perfectly plastic isotropic solid thereafter.

The investigations of the mechanism of contact between metal surfaces are also useful for clarifying the fundamental mechanism of friction and wear of metal as well as for solving the problems of fluid leakage between contact surfaces. It is clear that the series of the investigations made by Tsukizoe and Hisakado[19~22] have contributed to the interested field of engineering.

In this paper, the experimental results of air-leakage between contact surfaces are described. The specimens are

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finished by a machining which gives anisotropy to the surface roughness of metal.

The analytical results obtained in the previous reports, where the surface irregularities were assumed to be a form of truncated cone, are used to compare with them. The results obtained show that the analytical values of equivalent gap between contact surfaces are in agreement with the experimental values with deviation about 8 %, and that the characteristic curves of parameters a and b for the carbon steel listed in the 2nd report[13] can be applied for the materials tested in this experiment.

2. Nomenclature (see also the 1st and 2nd reports)

- $Hmax_0$: maximum height of surface irregularities without applied load
- hc_0: central height of surface irregularities without applied load
- hc: ditto (with applied load)
- 2γ: conical angle of truncated cones
- s: the ratio of bottom area of truncated cones to the upper area of truncated cones
- pc: applied load per apparently contacting area
- Hep: equivalent gap between contact surfaces with applied load
- $Hep(E)$: ditto (experimental values)
- $Hep(C)$: ditto (analytical values)
- $Hep(Cs)$: ditto (analytical values calculated by Eq. (14) of the 2nd report)
- $Hep(CB)$: ditto (analytical values obtained by replacing σs by σB in Eq. (14) of the 2nd report)
- σs: yield stress of specimen
- σB: tensile strength of specimen

3. Experimental apparatus and materials

The experimental apparatus and procedure and the form of specimen are similar to those used in the 2nd report. The mechanical properties, the machining of surface, the numerical values and the profiles of surface roughness of tested materials are respectively listed in Tables 1, 2 and 3 and are shown in Fig. 1.

In Table 3, the direction of surface tracing, mark l, of the specimens after grind-finishing coincides with the direction of grinding; therefore, the hc-values of this direction may be insignificant as the representative values of the surface contact condition in the leakage problem, hence they are not recorded. For the case of lathing, the hc-values in the directions of surface tracing, marks l, m and n, may also be excluded for the same reasons as above. The hc-values are automatically measured in "*the distance of the measurement of hc-value*" described in Fig. 1, where the measuring lengths in the directions of marks a, b and c are about 6 *mm* and those of marks l, m and n are about 10 *mm*. In other words, the hc-values can be quickly calculated by integrating automatically the area between the profiles of surface tracing and the base line of the recording paper of recorder simultaneously with tracing of the surface profile. This can be achieved by combined use of a surface roughness recorder, a digital integrator and a convertor devised by the author. The process of the measurement of hc-values is shown in Fig. 2. This can be divided into three groups, namely, (a) the circuit of convertor, (b) the action of convertor and (c) the expression of the calculation of hc-value.

Both actions of instruction and correction can be operated by the convertor.

Firstly, applying the flip-flop circuit included in Fig. (a), the pulsating curves shown in Fig.(b) can be recorded in the surface profile simultaneously with instructing of the necessary messages, start and stop, to the digital integrator.

At the same time, the digital integrator can compute automatically the area between the surface profile and the base line of recording paper in the interval of the pulses of start and stop. Secondly, the correction is made by electrically transmitting the output of the recorder to the digital integrator. The procedures are as follows; adjusting the variable resistances marked with ZVR and FVR in front of the constant-voltage electric power circuit included in Fig.(a), the zero and the maximum height of recording paper, i.e. 0 and 50 *mm*, respectively, (corresponding out-

Table 1 Mechanical properties of experimental materials

Materials		Mechanical properties				Heat treatment
Symbols	Notations	E kg/mm^2	σs kg/mm^2	σB kg/mm^2	Hardness HR	
Specimens	FC 15	1.0×10^4	11.3	17.0	B 86	Industrial scale
	BsBM2	0.98×10^4	31.0	40.0	B 61	ditto
	Cu B	1.3×10^4	∿	22.0	B 43	ditto
Base plate	SKS 2	∿	∿	∿	C 60	Oil quench

E : Young's modulus
HR: Rockwell hardness; B,C: Class of Rockwell hardness

puts of the recorder are -1.6 and +1.6 *volts*), can be converted to 0.000 and 5.000 *milli-volts* as the respective input values to the integrator. The relative values for the correction are listed in the table of Fig. (b).

Then, the *hc*-values can be calculated by the following procedure: (1) One draws the lines of *Hmax-Hmax* and *Ho-Ho* on the recording paper as shown in Fig. (b) according to the procedure described in the 1st report. (2) One obtains the area from the result by the digital integrator, using the conversion table shown in Fig. (b). (3) Then, the *hc*-values can be calculated by the expression described in Fig.(c). The corrections were performed before and after the measurement of the surface profiles, resulting in the accuracy less than 1 %, whereas the accuracy of the measurements done so far was several percent.

4. Experimental results and discussions

4.1 Values of γ and s

The characteristics of the distributions of γ-value are shown in Fig. 3 for the specimens finished by lapping. The similar results can be obtained with the specimens finished by grinding and lathing . Therefore, the γ- and the k-values of specimen may be considered to be determined by the mechanical properties of specimen and to be independent of the machining condition. The obtained γ- and k-values are listed in the table of Fig. 3.

The distributions of s-value are shown in Fig.4 for cast iron. The distributions for copper alloys are similar to those for cast iron, excepting that the s-values

Table 2 Machining methods for experimental materials

Symbols	Machining methods	Machining conditions
Specimens	Lapping	No. 240 of carborundum powder
	Grinding	Form of grinding wheel: WA60-KMV, 1750 rpm Depth of cut: 0.02 mm Feed speed: 60 cm/min.
	Lathing	FC 15:- Form of cutting tool: 6°, 0°, 10°, 7°, 30°, 60°, 5 mm, 40 rpm Depth of cut: 0.06 mm Cutting speed: 0.3 mm/rev BsBM2:- Form of cutting tool: ditto, 83 rpm Depth of cut: 0.05 mm Cutting speed: 0.04 mm/rev Cu B :- Form of cutting tool: 12°, -, 11°, -, -, -, 102 mm, 225 rpm Depth of cut: 0.04 mm Cutting speed: 0.025 mm/rev
Base plate	Lapping	Chrome oxide

Table 3 Numerical values of surface roughness; without applied load (μ)

Materials			Central height hc_0							Maximum height $Hmax_0$					
Symbols		Machining methods	Directions of surface tracing a	b	c	l	m	n	hc_{0mean}	Directions of surface tracing a	b	c	l	m	n
Copper alloy	BsBM 2	Lapping	5.70	6.07	6.24	6.64	6.85	6.25	6.29	11.5	13.6	12.6	14.5	13.5	14.0
		Grinding	2.29	2.12	2.41	-	3.02	2.76	2.52	4.9	4.4	4.3	-	5.0	5.8
		Lathing	4.79	4.34	4.42	-	-	-	4.52	10.5	10.0	10.0	-	-	-
	Cu B	Lapping	5.55	5.28	4.94	5.26	5.37	4.81	5.20	11.5	10.2	11.0	10.5	11.0	10.8
		Grinding	5.71	5.29	5.61	-	5.57	5.13	5.46	11.6	11.4	10.7	-	10.4	9.7
		Lathing	3.88	3.98	4.02	-	-	-	3.96	7.3	7.3	7.5	-	-	-
Cast iron	FC 15	Lapping	6.26	6.47	6.07	6.25	6.40	5.92	6.23	11.0	12.3	13.5	12.8	11.5	12.0
		Grinding	1.81	2.19	2.43	-	3.21	2.97	2.52	3.5	4.0	4.0	-	5.4	4.9
		Lathing	4.46	4.57	4.42	-	-	-	4.48	8.0	8.5	7.8	-	-	-
Base plate		Lapping	-							< 0.3					

Note: (1) Methods of measurement are shown in the 1st report
(2) On the working of grinding, the direction of surface tracing, i.e. mark l, coincides with that of grinding

corresponding to a large frequency tend to be a little lower for the copper alloys than for cast iron in any machining conditions employed in this experiment.

According to the results of this and the previous report, the *s*-values may be affected remarkably by the grain size of lapping powder, the depth of cut, cutting speed, etc., and they may be influenced by properties of materials to some extent.

In the case of specimens finished by grinding, it seems that the distributions of the *s*-values have a tendency to divide into two main groups. This may be due to the poor uniformity of the grain size of grinding wheel, which is similar to the case of lapped specimens described in the 2nd report. The obtained results of *s*-values are listed in Table 4.

4.2. Air-leakage

Examples of the experimental results are shown in Fig. 5. The load is applied by spring force in six steps from 1.0 to 30 kg/cm^2. The air-leakage is measured by increasing the supplied air pressure gradually until a sudden increase of air-leakage, the applied load being held constant.

It is evident that the air-leakage rate in the specimens finished by lathing is much less than in the specimens finished by grinding, though the *hc*-values of the former specimens are about 1.8 times larger than those of the latter ones as listed in Table 3. This will be discussed later in Section 4. 4. 2.

Reynolds number with respect to the equivalent gap is less than about 150, which means that the air-flow between the contact surfaces is a viscous flow under the limit of occurrence of turbulent flow.

4.3 Relation between equivalent gap obtained by experiments and supplied air pressures

The relations between the *Hep(E)*-values calculated by Eq. (25) of the 1st report and the supplied air pressure, i.e. pa^*, are shown in Fig. 6. The *Hep(E)*-values do not seem to vary until the balance condition between contact surfaces comes to be satisfied, as discussed in the 2nd report. The pa^*-values, at which the *Hep(E)*-values come to increase remarkably, depend on the machining methods, and are much the same for lapping and grinding, while they tend to slide to a somewhat high degree for lathing. When the supplied air pressure exceeds the pa^*-values mentioned above, the rate of increase of the *Hep(E)*-values of the specimens finished by lathing differs from those of the specimens finished by lapping and grinding; the former is smaller than the latter.

This is considered to be due to the difference in the mechanism of air-leakage between contact surfaces, which will be discussed in the following section.

In the case of specimens finished by lapping, the *Hep(E)*-values decrease about 0.5μm as the pa^*-values increase from 0 to 20kg/cm^2. This may be considered to occur as the result of the sealing effect due to the minute substances in the space between contact surfaces, as also discussed in the 2nd report.

4.4 Relation between equivalent gap and applied load

In Fig. 7 the *Hep(E)*-values are plotted against applied load.

4.4.1 Characteristics of parameters a and b obtained from analytical solution:

The *Hep(C)*-values which are calculated by Eq. (14) of the 2nd report are shown in Fig.7 with full lines, where the values of *Hep(Cs)* and *Hep(CB)* are represented by thin and thick full lines, respectively.

From the experimental results, the permanent reductions of the central height of surface roughness were found to be $\theta \geq 0.95$ at $pc \simeq 30 kg/cm^2$, hence the values of $\bar{\bar{\theta}}$ were taken to be unity for the calculations. It should be noted that the parameters a and b, which are calculated by Eqs.(7) and (8) of the 2nd report, can also be directly obtained by Figs.1 and 2 of the 2nd report. (The details are given in the Appendix 1).

4.4.2 Variation of the *Hep*-values by the machining methods

In the cases of the specimens finished by lapping and grinding, the *Hep(C)*-

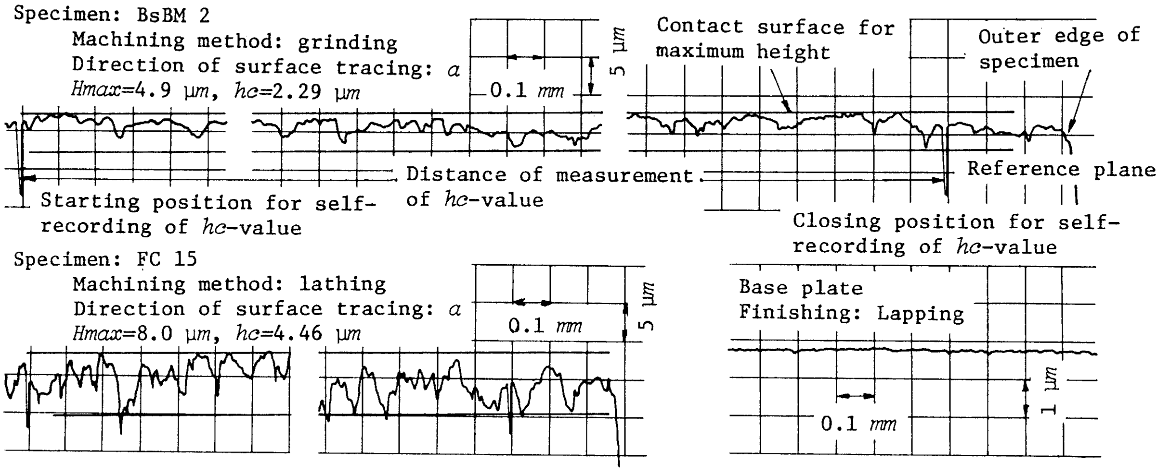


Fig. 1 Profiles of surface roughness of specimen and base plate (before the measurement)

values are in agreement with the $Hep(E)$-values with a deviation within about 8% in the range of the experiment for the variation of pc. If examined in detail, it may be found that the $Hep(CB)$-values come to agree well with the $Hep(E)$ rather than the $Hep(Cs)$ with an increase of applied load.

These results may be explained as follows: the deformation of surface irregularities is influenced by the tensile strength of specimen rather than the yield stress when the applied load increases.

This should be investigated in future under the conditions of a larger load than in these experiments being applied.

In the case of the specimens finished by lathing, the experimental results showed $Hep(C) \gg Hep(E)$. Then it was considered that the phenomenon of fluid leakage between contact surfaces should be confirmed.

In an experiment of pc=10 kg/cm^2, therefore, the leakage flows between contact surfaces were observed experimentally through an optical flat under the conditions of pc=∿1.0kg/cm^2 and pa*=0∿0.5kg/cm^2, the results being shown in Fig. 9. Some parts of the experimental apparatus for this experiment are reproduced in Fig. 8; alcohol mixed with blue ink and filtered through filter paper, was used as the fluid. The leakage flows in the specimens finished by lapping and grinding were recognized as radial inward flows, but those in the specimen finished by lathing were observed to have certain differences depending on the materials of specimen. In the case of brass, the leakage flow was a combined one of a whirl flow along the grooves curved by lathing and a sector flow at the outer (inlet) region of specimen, and it was composed of a couple of sector flows around the inner (outlet) region. In the case of cast iron, the leakage flow was similar to that in brass at the outer (outlet) region, while it became a sector flow around the inner outlet hole, where the wetted region spread nearly 180°. In the case of copper, the leakage flow was nearly a whirl flow throughout the contact surfaces of specimen but was not observed clearly around the inner outlet hole.

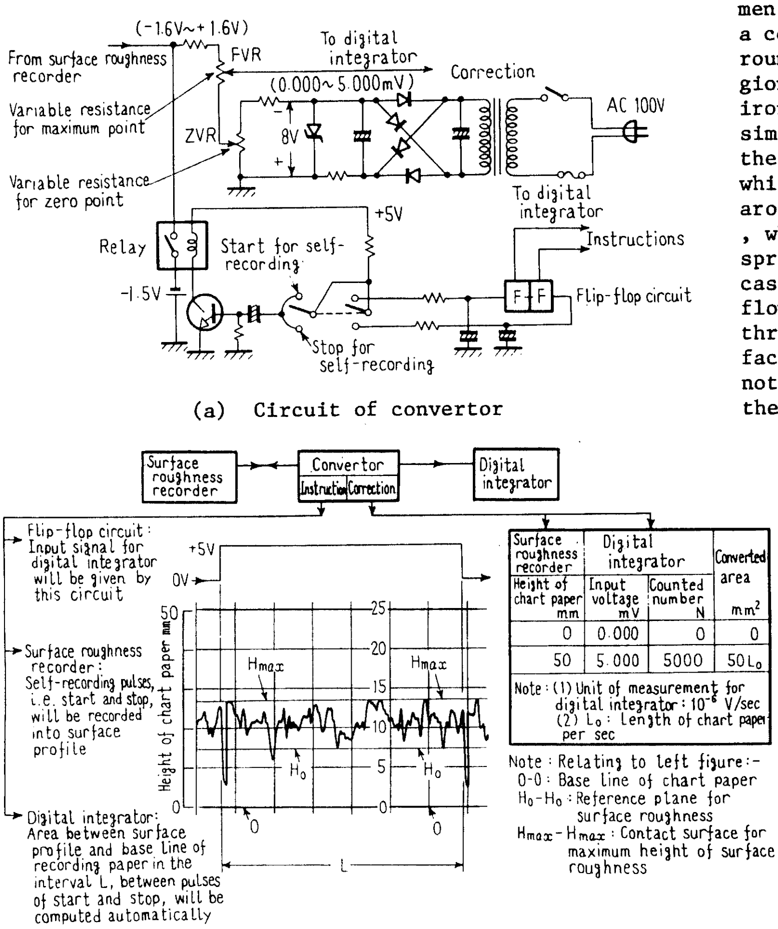
Now, assuming that the leakage flow between the contact surfaces is a viscous, laminar and isothermal flow in parallel surfaces with the equivalent gap with sector angle (radian), the total flow rate of leakage fluid is given by

$$Qi = \frac{\varphi(Hep)^3}{24\mu l_n roi} \frac{(pa^2-pi^2)}{pi} \qquad \cdots\cdots\cdots\cdots(1)$$

where, Qi: total flow rate of leakage air, μ : absolute viscosity of air, $roi=ro/ri$; ro: outer radius of specimen, ri: inner radius of specimen, pa: supplied air pressure, pi : outlet air pressure.

Substituting the value of $\varphi \simeq \pi$ obtained by the experiments for brass and cast iron into Eq. (1), the $Hep(E)$ can be obtained, and they are shown in Fig. 10 in comparison with the $Hep(C)$-values.

Though the sector angle φ might be var-



(b) Action of convertor (Instructions and correction)

(c) Expression of calculation of hc-value

$$hc = \frac{(A-B)}{L \times M} \times 10^3 \qquad (\mu m)$$

where,

A: Area for counted number N, i.e. area between surface profile and base line of chart paper among distance L, mm^2

B: Area between Ho-Ho and 0-0 among distance L, mm^2

L: Distance of measurement of hc-value, mm

M: Magnification of ordinate

Fig. 2 Procedure of automatical measurement of hc-value ied according to the applied load(see Appendix 2), it was assumed to be constant through the experiments. In the case of brass, the *Hep(C)*-values were in agreement with the *Hep(E)* with a deviation within about 7 %. The *Hep(CB)* agreed better than the *Hep(Cs)* with an increase of applied load, which is similar to the cases of lapping and grinding. In the case of cast iron, the deviation was about 20% at $pc \leq 5$ kg/cm^2, and the *Hep(CB)* and the *Hep(Cs)* became 10 and 15 %, respectively, when the applied load exceeded about 10kg/cm^2.

In the case of copper, the state of leakage flow around the inner outlet was not observed clearly, and so the discussions as mentioned above were not carried out.

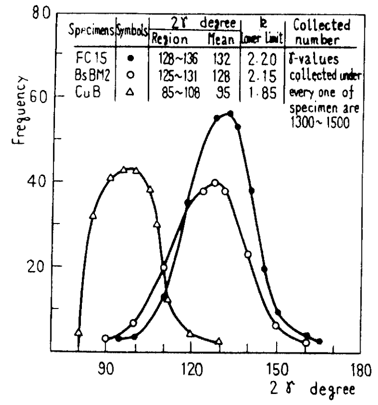


Fig. 3 Distribution of conical angles of surface irregularities (Finishing: Lapping)

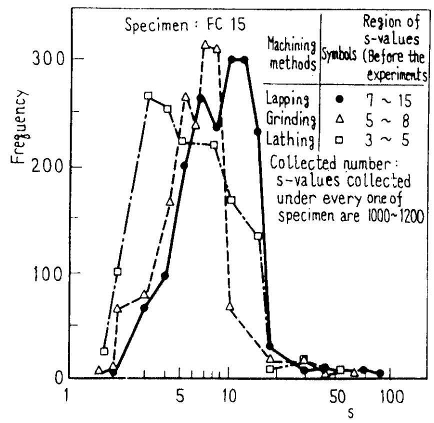


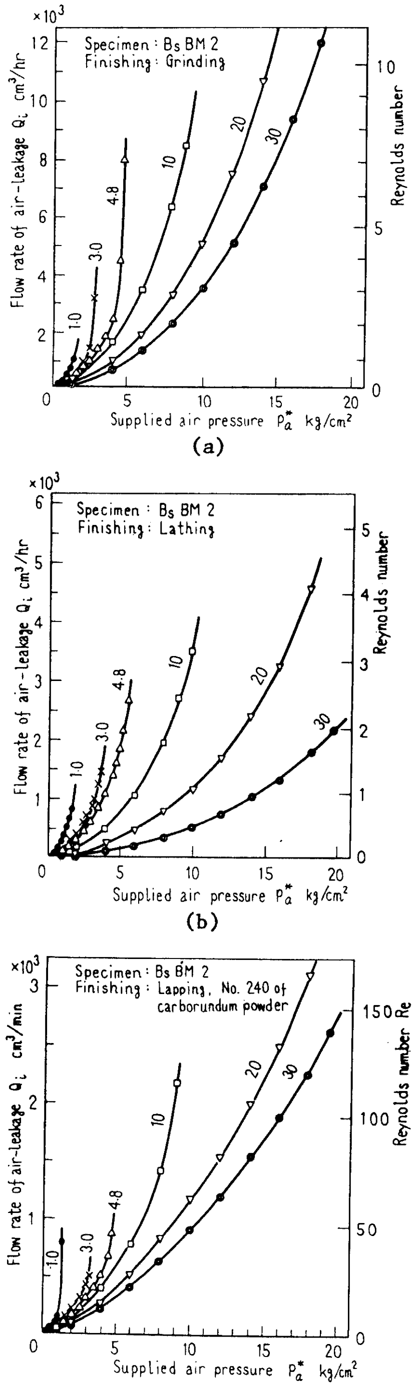
Fig. 4 Distribution of *s*-values (Before the experiments)

Table 4 Values of *s*

Machining methods	Specimens		
	FC 15	BsBM 2	Cu B
Lapping	10	8	8
Grinding	8	7	8
Lathing	5	3	3

The equivalent gap for the whirl flow, in other words, the phenomenon as observed with the specimen of copper finished by lathing should be investigated in future. Even if the specimen is finished by lathing, when cavity exists in some region of the contact surfaces of specimen, the leakage flow will become a radial one.

In this case, the experiments may show that *Hep(E)>>Hep(C)* as seen in Fig.11, which is an inverse relation to the results obtained above, and that the *Hep(E)*-



Note: Numerical values for every curve are applied load indicated in kg/cm^2

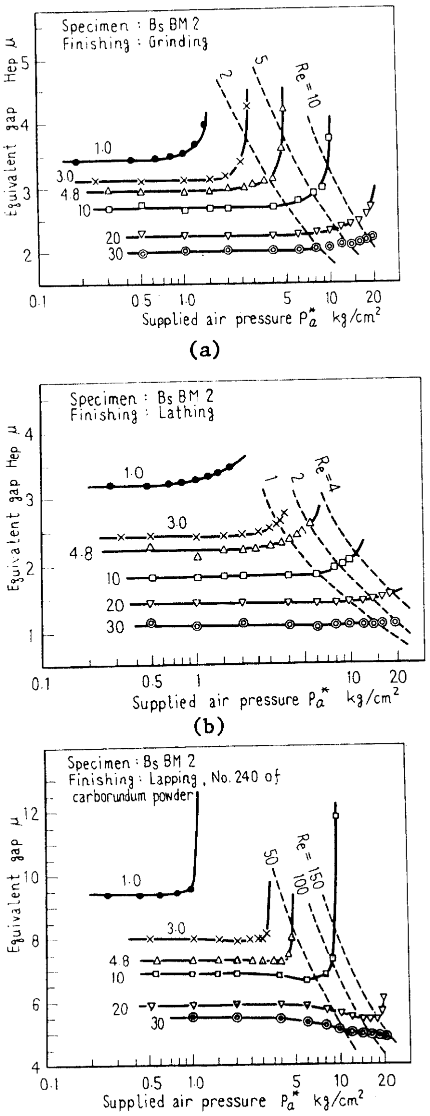
Fig. 5 Experimental results

values may not vary with the applied load.

The equivalent gap obtained analytically in the 1st and the 2nd reports is not applicable to the specimens having the surface roughness as mentioned above, in which the leakage flow through the cavity zone may account for most of the total quantity of leakage.

4.5 Balance condition between applied load and supplied air pressure

Substituting the experimental results into Eq. (20) of the 2nd report, the characteristics of balance condition can be obtained as shown in Fig. 12, where the frictional force of O-ring is taken to be 0.6∿1.0kg. Assuming that the leakage flow between contact surfaces is a radial one for the specimens finished by lapping, the balance conditions between applied load and supplied air pressure are in good agreement with the experimental results, where the analytical values of balance condition are $peq \equiv (pc/pa)$=0.83∿0.87 at pia =0.1∿0.5 for the specimen with the dimensions described in the 1st report. In the case of the specimen finished by grinding, the values of (pc/pa), when the leakage flow rate comes to exceed the degree of steady increase*, tend to deviate to a somewhat large value calculated from the peq-value, but this is not so distinctly recognizable that it may be concluded that a sudden increase of air-leakage occurs mostly under the balance conditions given by Eq.(20) of the 2nd report. In the case of leakage flow being a sector one such as seen with the specimen finished by lathing, the sudden increase of air-leakage occurs under the conditions of (pc/pa)=0.5 ∿0.6. Now, assuming that the leakage flow is a perfectly sector one and the sector angle is $\varphi=\pi$ radian, the balance conditions under which that peq becomes half of the former, yield (pc/pa)≃0.43 for pia=0.1 ∿0.5. This is different from the experimental results. It may be considered to be due to the fact that the real leakage flow is not a perfectly sector one as shown in Fig. 9, but the fluid pressure acts upon all the surface at the outer contact surface region. In the case of the leakage flow being a whirl one, however, the sudden increase of air-leakage occurs under the conditions of (pc/pa)=0.3∿0.4.



Note:
(1) Numerical values for every curve are applied load indicated in kg/cm^2
(2) Numerical values for every dotted line are Reynolds number

Fig. 6 Relation between supplied air pressure and equivalent gap obtained from experimental results

4.6 Elastic behavior rate, κ

Substituting the $Hep(E)$-values obtained by Fig.13 into Eq.(26) of the 1st report, the values of elastic behavior rate can be obtained as listed in Table 5, where the standard of applied load is 1.0 kg/cm^2. It can be seen that the deformations of the surface irregularities on the rough surface finished by lapping are fairly plastic under a low applied load just as in the results obtained by steel in the previous reports, but those of the surface irregularities on the minute surface finished by grinding and lathing have elastic property. Comparing the results with specimens of copper finished by lapping and the results of those by grinding, one can see that the numerical values of surface roughness are nearly equal to each other as listed in Table 3, and yet the ratio of the κ-values by grinding to that by lapping becomes 1.5∿1.7. This may show that the surface irregularities of the specimens finished by lapping have a considerably more plastic property than those of the specimens finished by grinding and lathing.

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*: The "steady increase" means the state that the leakage flow rate between contact surfaces increases proportionally to the values of pa^2, if the clearance between contact surfaces is not varied by the supplied air pressure.

5. Conclusions

In this paper, the leakage of fluid from the contact surfaces is studied experimentally. The specimens are made of cast iron or copper alloys, and they are finished by grinding, lathing or lapping; grinding and lathing are employed for the purpose to make clear the effect of anisotropy of surface roughness, and lapping is (for the purpose) to compare with them as this gives isotropy of surface roughness.

The results obtained can be summarized as follows:

(1) In the case of the specimen finished by grinding, the *Hep(C)*-values calculated by the analytical solutions obtained in the 1st and the 2nd reports agree well with the *Hep(E)* obtained from the experimental results with a deviation within about 8 % in the region of $pc \leq 30 kg/cm^2$. It seems that the *Hep(CB)*-values agree comparatively well with the *Hep(E)* rather than the *Hep(Cs)* with an increase of applied load.

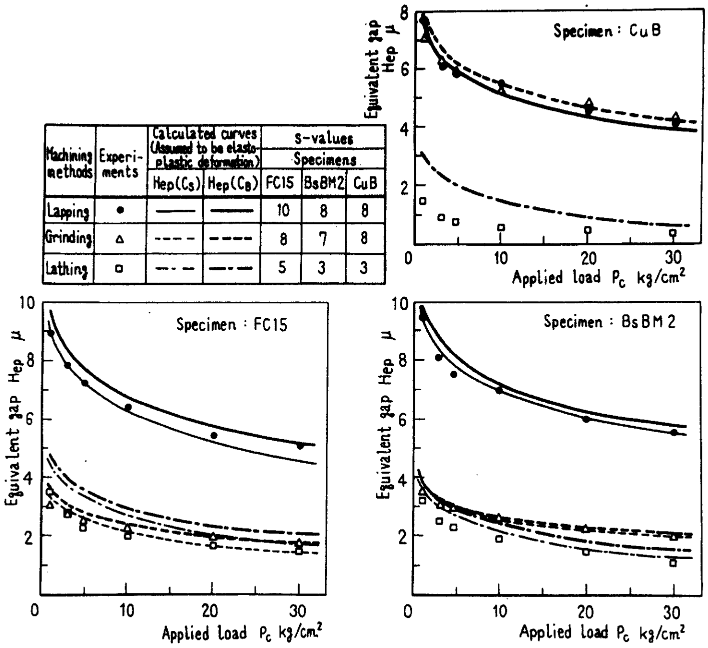
These results may be valid with the specimen finished by lapping. The leakage flow is a sector or a whirl one in the contact surfaces of the specimen finished by lathing, excepting under the condition of a cavity existing in some region of the surface of the specimen.

In the case of the sector flow, the deviation of the *Hep(C)*-values from the *Hep(E)*-ones becomes 7~10%. The relations of the *Hep(Cs)*-ones and the *Hep(CB)* ones versus the *Hep(E)*-ones are similar to the above results obtained with the specimens finished by grinding when the applied load increases.

In the case of whirl flow, the state of leakage flow around the inner outlet hole of specimen was not observed clearly, and so the discussions as above were not carried out. This will be investigated in future.

(2) The characteristic curves of parameters *a* and *b* obtained for carbon steel, which were shown in the 2nd report, can be applied to the materials tested in this experiment.

(3) The analytical expression of the balance condition between applied load and supplied air pressure between contact surfaces, which was described in the 2nd report, is in good agreement with the exper-



Machining methods	Experiments	Calculated curves (Assumed to be elasto-plastic deformation) Hep(C_S)	Hep(C_B)	s-values Specimens FC15	BsBM2	CuB
Lapping	●	——	——	10	8	8
Grinding	△	----	----	8	7	8
Lathing	□	-·-·-	—·—	5	3	3

Fig. 7 Relation between applied load and equivalent gap

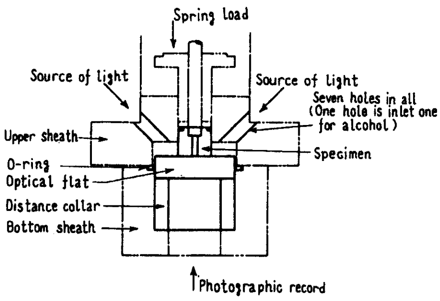
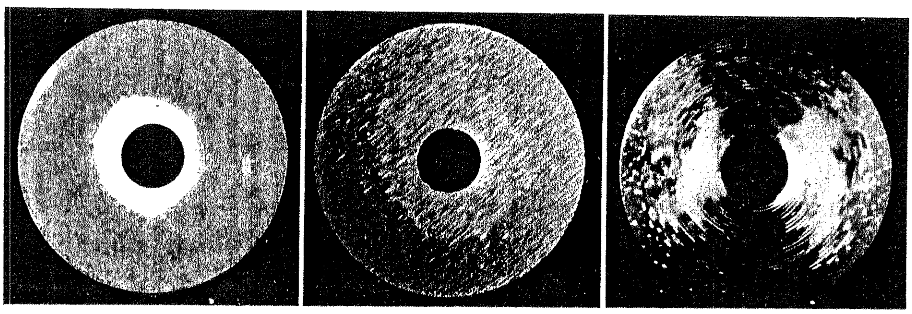
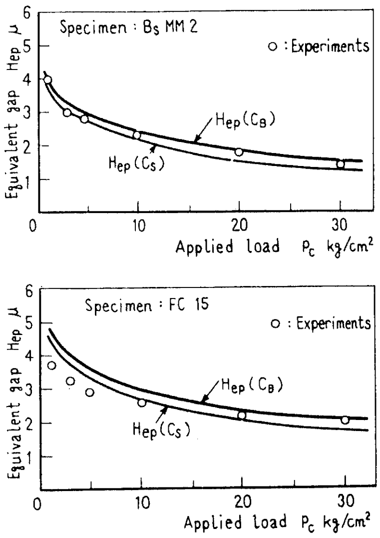


Fig. 8 Procedure of observation of leakage flow between contact surfaces



Finishing: Lapping (Specimen: BsBM 2) Finishing: Grinding (Specimen: FC 15) Finishing: Lathing (Specimen: BsBM 2)

Fig. 9 Photographs of leakage flow between contact surfaces



Note:
(1) Specimens are finished by lathing
(2) The values of equivalent gap by experiments are calculated under the assumption that sector flow occurs in space between contact surfaces

Fig.10 Relation between applied load and equivalent gap with the consideration of phenomenon of leakage flow

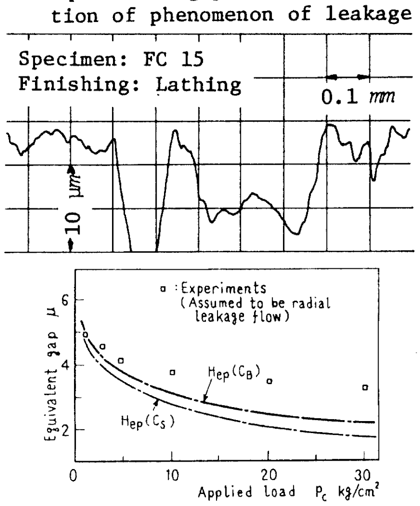


Fig.11 Comparison of the experimental and the calculated values of equivalent gap, where cavity exists in some region of the contact surface of specimen and the surface roughness is rough

imental results using the specimens finished by lapping and grinding. It may be concluded that, when the radial leakage flow occurs in the space between contact surfaces, the expression of the balance condition is valid in any machining methods.

(4) It seems that the deformation of the surface irregularities of the specimen finished by lapping tends to be more plastic than that of the specimens finished by grinding and lathing under a comparatively low applied load, i.e. nearly 30 kg/cm^2, while that of the specimen finished by grinding or lathing tends to be elastic, where the surface roughness is a minute one.

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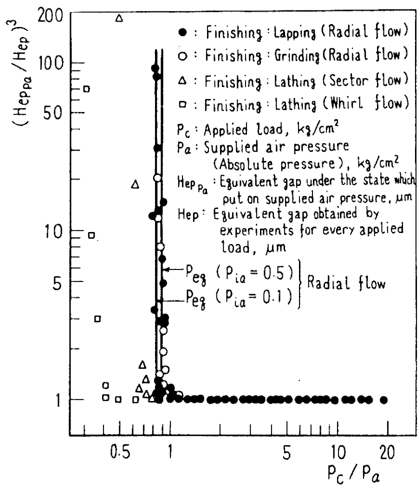
Appendix 1



Note: Leakage flow between contact surfaces is assumed to be radial one

$$peq \equiv (pc/pa) = \sqrt{\frac{a}{2}}\,\pi\frac{e^{-\frac{2}{b}}}{Sn}\sum_{n=0}^{\infty}\frac{1}{n!}\frac{2}{(2n+3)}t^{n+\frac{3}{2}}\Bigg|_{t=\frac{2}{b}(1+l_n ri)}^{t=\frac{2}{b}(1+l_n ro)}$$

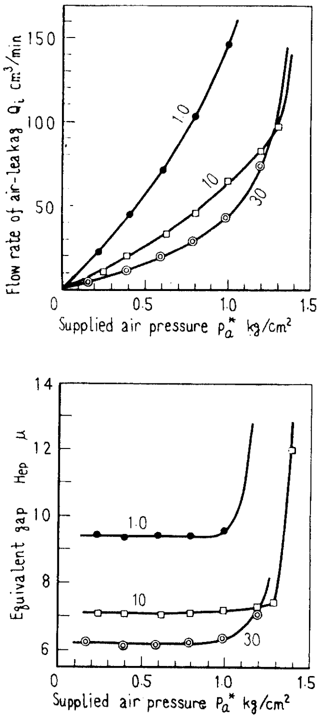
Fig. 12 Balance conditions between applied load and supplied air pressure

Table 5 Elastic behavior rate for cast iron and copper alloys

Applied loads	Elastic behavior rate κ % (Applied load of standard; pc=1.0 kg/cm^2)								
pc	FC 15			BsBM 2			Cu B		
kg/cm^2	Lapping	Grinding	Lathing	Lapping	Grinding	Lathing	Lapping	Grinding	Lathing
10	27	61	58	8	60	52	18	30	-
30	29	68	60	18	65	55	22	33	-

Note: The above results are obtained by assuming that the leakage flow between contact surfaces is radial for the specimens finished by lapping and grinding, and sector for those finished by lathing, respectively.

The values of $\Theta(\beta)$ for various values of β are listed in Table 6. The values of $I(\beta)$ obtained by applying the values of parameters a and b, which are obtained by introducing the values of $(E/k\sigma s^*)\{\sqrt{s}/(\sqrt{s}-1)^2\}$ and s into Figs. 1 and 2 of the 2nd report, are listed in Table 7, where the term distinguished by an asterisk may correspond to σs or σB. The characteristic curves for the equivalent gap between contact surfaces are shown in Fig.14 obtained by replacing $\Theta(\beta)$ by $I(\beta)$. As the result, the characteristic curves of parameters a and b for carbon steel listed in the 2nd report are applicable to the materials such as cast iron and copper alloys.



Specimen: BsBM 2

Finishing: Lapping, No.240 of carborundum powder

Note: (1) Every one of applied load is $pc=1.0\ kg/cm^2$

(2) Numerical values for every curve are increased applied load indicated in kg/cm^2

Fig.13 Experimental results with constant applied loads after the increased applied loads were applied in order of magnitude

Appendix 2

When the surface of specimen includes abnormally high surface irregularities and if it satisfies either condition of: (1) the abnormally high surface irregularities are distributed on one side of apparent contact surfaces or (2) the real contact pressures are extremely unbalanced in their distribution, then the tendencies of the contact surfaces may be varied by a small variation of nominal applied load so that the values of φ may be varied with the pc-values.

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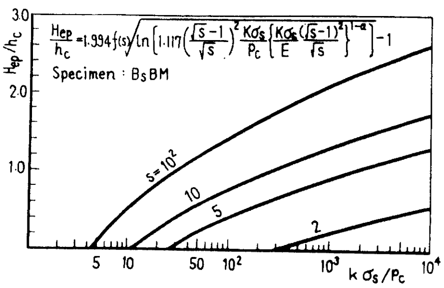

Fig. 14 Characteristic curves: assumed that the deformation of truncated cone is elasto-plastic

Table 6 $\Theta(\beta) = \{\Psi(\beta)/\chi\} - K(\beta)$

Specimens	FC 15 ($E=1.0\times10^4\ kg/mm^2$, $\sigma s=11.3\ kg/mm^2$, $\sigma B=17.0\ kg/mm^2$, k=2.20(Lower limit))				BsBM 2 ($E=0.98\times10^4\ kg/mm^2$, $\sigma s=31.0\ kg/mm^2$, $\sigma B=40.0\ kg/mm^2$, k=2.15(Lower limit))				CuB ($E=1.3\times10^4\ kg/mm^2$, $\sigma B=22\ kg/mm^2$, k=1.85 (Lower limit))	
s	3		10		3		10		3	10
β \ σ*	σs	σB	σs	σB	σs	σB	σs	σB	σB	
0.2	942.237	625.893	196.194	129.994	343.629	266.033	70.926	54.687	747.931	155.532
0.4	655.030	435.154	136.491	90.478	238.966	185.032	49.422	38.136	519.977	108.229
0.6	433.555	288.047	90.398	59.948	158.214	122.522	32.778	25.309	344.180	71.695
0.8	271.887	180.650	56.720	37.627	99.242	76.862	20.591	15.907	215.847	44.992
1.0	160.839	106.873	33.569	22.276	58.720	45.483	12.199	9.429	127.692	26.632
1.2	89.392	59.401	18.663	12.387	32.641	25.284	6.787	5.248	70.971	14.808
1.4	46.519	30.913	9.715	6.449	16.988	13.160	3.535	2.734	36.933	7.709
1.6	22.742	15.113	4.751	3.155	8.307	6.435	1.730	1.339	18.056	3.771
1.8	10.397	6.909	2.173	1.443	3.798	2.942	0.792	0.613	8.255	1.724
2.0	4.419	2.937	0.924	0.614	1.615	1.251	0.337	0.261	3.509	0.733

Note: The term distinguished by an asterisk, i.e. σ*, means σs or σB

Table 7 $I(\beta) = \left\{\frac{k\sigma^*}{E} \frac{(\sqrt{s}-1)^2}{\sqrt{s}}\right\}^{-a} e^{-b\beta^2}$

Specimens	FC 15				BsBM 2				Cu B	
σ*	σs	σB	σs	σB	σs	σB	σs	σB	σB	
a	0.908	0.903	0.882	0.872	0.893	0.888	0.854	0.845	0.905	0.877
β \ b	1.374	1.374	1.372	1.372	1.374	1.374	1.372	1.372	1.374	1.372
0.2	636.241	424.505	132.908	88.009	232.598	179.853	48.097	37.205	505.409	105.569
0.4	539.533	359.980	112.732	74.649	197.243	152.516	40.795	31.557	428.587	89.543
0.6	409.895	273.485	85.680	56.736	149.850	115.869	31.006	23.984	325.607	68.056
0.8	279.025	186.168	58.350	38.638	102.006	78.875	21.116	16.334	221.648	46.348
1.0	170.128	113.511	35.607	23.578	62.196	48.092	12.885	9.967	135.144	28.283
1.2	92.944	62.013	19.469	12.892	33.978	26.273	7.046	5.450	73.831	15.465
1.4	45.490	30.352	9.539	6.317	16.630	12.859	3.452	2.670	36.136	7.577
1.6	17.778	11.862	4.188	2.773	6.499	5.026	1.516	1.172	14.122	3.327
1.8	7.836	5.228	1.648	1.091	2.865	2.215	0.596	0.461	6.225	1.309
2.0	2.758	1.840	0.581	0.385	1.008	0.780	0.210	0.163	2.191	0.461
s	3		10		3		10		3	10

Note: (1) The term distinguished by an asterisk, i.e. σ*, means σs or σB
(2) For $0.6 \leqq \beta \leqq 1.4$; error $\leqq 6$ %

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