Visualisation of the real contact area at gasket surfaces using thin PC films

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Abstract

Leakage rates and real contact areas of the seal surfaces were measured under several closing loads. The static seal consisted of a ring-shaped copper gasket and the two carbon steel flanges, the surfaces of which were finished on a lathe. With increasing closing load, the leakage flow in the radial direction ceased and only that in the circumferential direction remained. To determine the closing load at which radial leakage flow ceases, it is necessary to determine the real contact conditions on the gasket surface. In the present study, the real contact area between the copper gasket and the steel flange was measured using a thin polymer film 1 \textmu m in thickness. The contact pressure over which the radial leakage ceased could be predicted from observations of the thin polymer film. In addition, the cross-section of the channel for leakage flow in the circumferential direction was evaluated from the measured real contact area, and the leakage rates were estimated by assumption of laminar flow. The results agreed well with the measured leakage rates.

Keywords: tribology, coupling, flat metallic gasket, leakage, thin polymer film, real contact area, surface roughness, gas leak test.

1 Introduction

Solid metal flat ring gaskets are used extensively in industry where, depending on the process medium, temperature, pressure and/or allowable leakage rate, soft materials (or combination gaskets consisting of soft material with metal) cannot be used. It is difficult to estimate leakage rates accurately, as both the flanges and
the gaskets have rough and undulating mating surfaces. The distribution of the real contact area between the flange and the gasket is complicated. Thus, the leakage paths cannot be specified. Under such conditions, metallic gaskets are likely to be selected experientially.

Table 1: Mechanical properties.

<table>
<thead>
<tr>
<th></th>
<th>Tensile strength $\sigma_B$ [MPa]</th>
<th>Elongation $\varepsilon$ [%]</th>
<th>Hardness Hv</th>
<th>Heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flange</td>
<td>490</td>
<td>38</td>
<td>234</td>
<td></td>
</tr>
<tr>
<td>SS400</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gasket</td>
<td>212</td>
<td>61</td>
<td>46</td>
<td>560°C, 1hr vacuum annealing</td>
</tr>
<tr>
<td>C1100</td>
<td></td>
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Tanaka and Yamashita [1] deduced the theoretical formula to calculate the leakage rate from the metal flange-gasket interface taking the contact mechanics between randomly rough surfaces into consideration. Frêne et al. [2] measured the real contact area over only a fraction of the apparent contact area. A seal associated with solid contact is meaningless if the whole contact surface is not observed simultaneously.

In the present study, we measured the real contact area between the flanges and gaskets using the polymer film method developed previously by one of the authors, Nitta [3, 4]. The sealing characteristics were tested with a combination of a lathe-turned steel flange and polished copper gasket to measure the leakage rates as a function of the bolt load. The leakage paths were determined based on the distributions of the real contact area measured by the polymer film method. The leakage rates through the flange and gasket interface were calculated under the assumption of laminar flow. The calculated leakage rates showed good agreement with the real measured values.

Figure 1: Shapes and dimensions of the specimens.
2 Experimental details

2.1 Specimens

Figure 1 shows shapes and dimensions of the carbon steel flange and copper gasket used in the leakage tests. The steel flange was of the raised face type with a flat mating face, but the portion inside the boltholes was raised. The copper gasket was of the ring type and was placed entirely within the boltholes of the flange. The flange surfaces were lathe-turned with a cemented carbide cutting tool with a nose radius of 1.2 mm and a feed rate of 0.27 mm/rev. The copper gasket surfaces were polished with fine abrasive cloths and annealed under vacuum prior to the experiments. Table 1 shows the mechanical properties of the flanges and the gaskets. The surface roughnesses of the flange surface and the gasket surface are shown in Fig. 2. The maximum roughness of the flange surface was 11.5 µm and that for the gasket surface was 1.5 µm.

2.2 Test apparatus for sealing characteristics

A cross-section of the experimental apparatus used to examine the sealing characteristics is shown in Fig. 3. The copper gasket was sandwiched between the upper and lower flanges. Usually, bolt load is applied to the flanges by torquing the bolts. Ideally, it was desirable for the four bolt loads to be the same at all time points in the experiments to measure the real contact area by the polymer film method. However, such loading is impossible in reality. Thus, instead of bolts, four hydraulic cylinders connected to the same hydraulic pump were used to apply the normal loads to the upper flange. As a carrier gas, helium was introduced into the chamber containing the gasket and the flanges at a pressure of 39 kPa and carried away any detecting gas to a gas chromatograph. As the detecting gas, nitrogen was introduced into the chamber at a pressure of 882 kPa. If leakage of helium gas occurred at the gasket and flange interface, the detecting gas passed into the chamber through the leakage paths, and was taken to the gas chromatograph by the carrier gas, Matsuzaki et al. [5]. The relationship between the amount of leakage of the detecting gas and the signal of the gas chromatograph was calibrated prior to the experiments.

![Surface roughness of the specimens.](image)
2.3 Measurement of real contact area by the polymer film method

The polymer film method is used to measure the real contact area between two solid surfaces by insertion of a thin polymer film between them, and transferring contact marks onto the polymer film surface. A polycarbonate film 1 µm in thickness, made by the spin coating method in our laboratory, was inserted between the flange and gasket interface and pressed at the given contact pressure for one minute. Micro asperities on the flange surfaces penetrated the polymer film and plastic deformation occurred on the film at the real contact points between the flange and the gasket. After unloading, the polymer film was removed from the interface and the indented area was observed under a microscope to measure the real contact area.

3 Experimental results

3.1 Sealing characteristics

Figure 4 shows the relationships between the leakage rate $Q_0$ (at a standard pressure of 0.101 MPa and a standard temperature of 0°C) and the normal pressure applied to the gaskets. The experiments were repeated three times under the same conditions to check reproducibility. In every experiment, a new gasket was used and the upper and lower flanges were reused. The leakage rates were reduced rapidly with contact pressure up to 40 MPa. The reduction rate became slightly smaller over 40 MPa. In addition, the leakage rates were reduced rapidly again over 90 MPa. The leakage rates were $10^{-5}$ L/h or less over 120 MPa. At such a leakage rate, it would take 11.4 years for leakage of 1 L of gas. Therefore, we considered that there was almost no leakage when the gasketed joints reached this leakage rate. The reproducibility of the experiments was acceptable although these experiments were slightly different to each other. Thus, the loading process could be divided into the three following domains: (1) a domain where the leakage rates decreased rapidly; (2) a domain where the leakage rates decreased moderately; and (3) a domain where the leakage rates again decreased rapidly.
Next, experiments were conducted to investigate the gas flow state thorough the flange and gasket interface in the leakage domain (2).

![Figure 4: Leakage as a function of contact pressure.](image)

3.2 Measurement of real contact area by the polymer film method

The indented area on the polymer film representing the real contact points between the flange surface and the gasket surface was observed over the whole apparent contact area. Contact occurred uniformly across the entire apparent contact area although there were slight undulations in the contacting surfaces. Therefore, the observation of the real contact area was restricted to a region of 20-degree central angle, as shown in Fig. 5. The real contact area was measured by image processing, and the region was divided further into smaller regions of one-degree central angle due to restriction of the field view of the optical microscope.

![Figure 5: Contact marks on the PC film and how to measure them.](image)

Black portions in Fig. 6 indicate the measured real contact area. Figures 6(a), 6(b), 6(c) and 6(d) show the measured values at contact pressures of 5 MPa,
12.5 MPa, 50 MPa and 100 MPa, respectively. We expected that the clear spiral marks on the flange surfaces were transferred to the polymer films. At a contact pressure of 5 MPa, there appeared to be almost no real contact area near the inner side of the gasket and several discontinuous curves were observed near the outer side of the gasket. At 12.5 MPa, the contact marks became clearer near the inner side of the gasket, although the contact marks were still discontinuous. Thus, at this contact pressure leakage flow in the radial direction perpendicular to the lathe-turned groove would be expected as well as along the groove. Clear continuous contact marks were obtained at a contact pressure of 50 MPa. At 100 MPa, the contact marks became thick and were doubled with new contact marks appeared between the old marks. From the surface roughness of the flange surface shown in Fig. 2(b), the second peaks at a height of 0 µm can be seen to be responsible for the double contact marks.

![Figure 6: Measured contact marks.](image)

Figure 7 shows the distribution of the real contact area measured by the polymer film method in the radial direction of the gasket. The abscissa of this figure shows the positions of the contact marks, i.e., the number of contact marks, starting from the inner peripheral side of the gasket. Thus, “n1” indicates the first contact mark from the inner peripheral side of the gasket and “n19” indicates the 19th contact mark located in the vicinity of the outer periphery of the gasket. The gasket width in the radial direction was 5 mm and the feed rate of the flange surface was 0.27 mm/rev. Therefore, 18 or 19 of the contact marks...
would appear on the polymer films. At a contact pressure of 12.5 MPa, there was no or less contact area near the inner side. When the contact pressure was increased to 50 MPa, the contact area was almost the same from the inner to the outer side. At 100 MPa, the contact area increased almost monotonically from the inner to the outer side, although the real contact area became larger at the inner side of the gasket surface.

![Figure 7: Real contact area at each contact mark.](image1)

![Figure 8: Contact pressure calculated by FEM.](image2)

Figure 8 shows the contact pressure distributions on the gasket surfaces in the radial direction analysed by the elastic finite element method (FEM). In FEM analysis, we assumed that there was no surface roughness and no friction on the mating surfaces. The bolts were eliminated from the FEM mesh. Thus, the normal load was not applied to the bolts but to the node points along the boltholes on the flanges. Dotted curves show the contact pressure distributions in the radial direction, including the bolthole, *i.e.*, along the horizontal centreline of the flange shown in Fig. 1(a), while solid curves show the contact pressure distributions between the boltholes, *i.e.*, along the line with the central angle...
inclined at 45° from the horizontal centreline. The abscissa shows the position of the gasket width, ranging from 0 mm to 5 mm. The ordinate in Fig. 7 represents the real contact area. However, it can be transformed into the real contact pressure by multiplying by the plastic flow pressure. Thus, the distribution curves in Figs. 7 and 8 can be compared with each other although the units of the coordinates are different. The tendency of changes in the distribution of the real contact area were similar to those of the changes in the distribution of the contact pressure in Fig. 8 at a contact pressure of 75 MPa or 100 MPa.

The surface asperities on the machined surfaces affect the distribution of contact pressure. In almost all cases, they act to flatten the distribution of contact pressure. However, if the contact pressure becomes high and plastic deformation of the surface asperities is saturated, the contact pressure will approach the analytical value without consideration of surfaces roughness. This tendency was seen in this experiment as shown in Fig. 7. At a contact pressure of 50 MPa, the distribution of contact pressure became almost flat. It differed greatly from the calculated value as shown in Fig. 8. Thus, the distribution of real contact pressure cannot be estimated accurately in elastic analysis, which does not take surface roughness into consideration, especially when the contact pressure is low.

4 Discussion

To estimate the leakage rates at contact pressures over 40 MPa, a gas flow channel sandwiched by a serrated flange surface and an ideal flat surface was assumed as shown in Fig. 9. In this figure, the width of the channel, w, was determined by the polymer film method. The hatched area in this figure shows the cross-sectional area of the flow channel whose value was calculated based on the cross-section curves obtained with a stylus profilometer as shown in Fig. 2(b). To calculate the leakage rates by equ. (1) on the assumption of viscous laminar flow, the gas flow channel was transformed into a rectangular channel with the same section area as shown in Fig. 9. The height of the rectangular channel, h, was defined by dividing the section area, A, by the width of the channel, w.

\[
Q_0 = \frac{wh^3}{24\mu p_2 L}(p_1^2 - p_2^2)
\]

where, w is the width of the flow channel, h is the height of the channel, \(\mu\) is the coefficient of viscosity of nitrogen gas, L is the length of the channel, \(p_1\) is the inlet pressure, and \(p_2\) is the outlet pressure.

The calculated results are shown in Fig. 10, which shows a curve indicated by “PC film”. The three dotted curves in this figure are the measured values. The calculated values were in good agreement with the measured values from around 40 MPa to 100 MPa. The calculated values were lower than the measured values
at pressures below 40 MPa because equ. (1) does not take the leakage flow in the radial direction into consideration.

Figure 9: Channel form for the leakage calculation.

The leakage rates were calculated based on slip line field theory with consideration of the work-hardening effect, Nitta et al. [6]. They are shown in Fig. 10, indicated by “S.L.F(truncated)” and ”S.L.F”. In the case of “S.L.F” in which the plastic flow of the gasket material into the channel was considered, the calculated values were in good agreement with the experimental values. This was because slip line field theory could accurately estimate the plastic flow pressure of the gasket material at the real contact points.

5 Conclusions

To clarify the sealing characteristics of the flat metallic gasket, the leakage rate and real contact area of the seal surfaces were measured by the polymer film method. This allowed determination of the contact pressure at which radial leakage flow ceased. The following results were obtained.

(1) At contact pressures of less than 40 MPa, the ridges on the flange surfaces were brought into local contact. The gas flow in the radial direction other than
that along the spiral grooves markedly affected the leakage rates. However, the ridges on the flange surfaces were brought into continuous contact at pressures over 40 MPa and only the flow along the spiral groove remained.

(2) The leakage rates were estimated based on the real contact area measured by the polymer film method. The calculated leakage rates were in good agreement with the measured values from contact pressures around 40 MPa to 100 MPa.

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References


