On the Assessment of Lubricity in the Deformation Process
by a Strip-ironing Type Friction Testing Machine*
(Fundamental Considerations and Measurements of Anti-weldability)

By Nozomu KAWAI**, Tamotsu NAKAMURA*** and Shigeyuki MIYAMOTO****

A strip-ironing type friction testing machine, which can measure simultaneously normal and frictional forces acting on the die during the process, has been made on an experimental basis to assess an ability of lubricants to resist the welding at the tool-work interface in deformation processes. It can estimate effects of the bulk plastic deformation of metal; i.e., an increasing ratio of the frictional surface area \( \eta \) and a sliding distance \( h \) on the welding which are important factors for the welding phenomena of the deformation process. To measure anti-weldability by this testing machine, paraffinic mineral oils have been tested with a commercially pure aluminum strip. The following conclusions were made. (1) The frictional coefficient \( \mu \) and the average frictional shear stress can be expressed by the ratio of the welding area to the total contact area. (2) The ability to resist the welding of lubricants can be assessed by the contour lines of \( \mu = \text{constant} \) on the \( \eta - h \) diagram.

1. Introduction

Tools and work metal interfaces in deformation processing are apt to weld together relatively easily during the process, because (a) the interfaces tend to be under boundary lubrication conditions in most cases, and (b) the work metal surface expands due to the bulk plastic deformation\(^{1}\). Since the welding causes irreparable damage to the tool and work metal surfaces, its prevention is essential.

Hitherto, some investigations on the welding phenomena in deformation processes have been reported by H. Wiegand et al.\(^{2}\), S. Fukui et al.\(^{3}\), T. Sudo et al.\(^{4}\) and Oyane et al.\(^{5}\). These works have examined qualitatively the effects of various factors, such as tool materials, sliding distance and sliding velocity on the welding. However, critical conditions for the occurrence of the welding have not been clarified quantitatively thus far.

In the previous papers\(^{6}\)-(\(^{7}\)), the authors have confirmed using a two-dimensional drawing type friction testing machine that the frictional coefficient under the boundary lubrication was an approximately constant value fixed by the type of lubricants independent of pressure between the tool and work, that the welding phenomena were facilitated by the surface expansion of work metal during the process, and that the frictional shear stress acting on the welding region was a constant value approximately equal to the yield shear stress of the work metal. Moreover, some measurements were proposed to assess the anti-weldability of lubricants. However, it has been recognized that the reduction (i.e., the degree of the surface expansion) and the drawing travel (i.e., the sliding distance obtainable by the apparatus used) were not sufficient to examine the anti-weldability.

In the present investigation, a strip-ironing type friction testing machine has been newly designed as a means to overcome

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\( S_0 \): Area of frictional surface before ironing
\( S_f \): Area of frictional surface after ironing
\( r \): Reduction
\( \eta \): Increasing ratio of frictional surface area
\( \eta = (S_f - S_0)/S_0 = (t_f - t_0)/t_0 \)
(in case of plain strain)

Fig. 1 Principle of ironing process
the drawbacks of the drawing type machine. Using this machine, the phenomena by which aluminum work metal welds together with the steel tool have been examined in details and on the basis of the results, a new method to assess the anti-weldability in the deformation process has been proposed.

2. Experimental conditions

2.1 Experimental apparatus

Figure 1 shows the principle of the apparatus. A workpiece strip is by being pulled upwards together with a back-up plate. When a frictional resistance $F_c$ acting on the interface of the strip and the back-up plate increases, a tensile stress acting on the ironed strip can be reduced and the ironing reduction is improved. The strip-ironing type friction testing machine in the present work has been devised so as to increase as much as possible the sliding distance and the reduction of work metal based on the above principle.

Figure 2 shows an assembly drawing of the main parts of the apparatus, which is mounted on the bed of a tensile-type hydraulic press. The latter has a maximum loading capacity of 98 kN and a maximum ram stroke of 600 mm. The workpiece is drawn up together with the back-up plate by a chuck. The frictional force and the normal force acting on a die surface are detected electrically by strain gauges attached to the elastic beams and, and recorded simultaneously. The strain gauges are fixed throughout the ironing process. Thus, the former can be detected as a tensile strain of the beam, and the latter as a compressive strain of the beams and. The bending strain of due to the normal force and those of and due to the frictional force cancel out under the output of the strain gauges of cold-rolled sheet on both sides of the beams. Thus, the interference between both forces can be removed. It has been confirmed by the calibration of measuring device that a linear relation holds between the load and the output during both the loading and the unloading process within ranges up to the respective maximum capacities which are 24.5 kN for the frictional force and 59 kN for the normal force, and that the interference is negligibly small, namely, about $\pm$ 1.5% for each full scale.

2.2 Experimental procedures

Table 1 shows the working conditions. The ironing reduction can be easily changed by adjusting the clearance between the die and the back-up plate. The die angle can be set at $5^\circ$, $10^\circ$, $15^\circ$, $20^\circ$ and $25^\circ$ by transferring to appropriate positions the three pins to fix the measuring device. A standard die angle used in the present experiments is $10^\circ$. To make the sliding distance as long as possible, a hydraulic press with a relatively large ram stroke (600 mm) has been used. Thus, a maximum ironing stroke of 350 mm has been obtained as a standard condition. The ironing velocity can be changed within the range of 0 - 10 mm/s. To remove a hydrodynamic effect of lubricants, a relatively low velocity 1 mm/s is used in the present experiments. A back-up plate finished with a file-like surface ($R_{\text{max}} = 150 \mu m$) is used as a standard in order to increase the frictional force. The workpieces with width of 20 mm are cut to a length 450 mm in the rolling direction from cold-rolled sheet of commercially pure aluminum (A1050) 2 mm thick, and thereafter fully annealed ($350^\circ C$, 1 h).

The expansion rate of work metal surface $n$ which appears during the ironing process is

<table>
<thead>
<tr>
<th>Tool</th>
<th>Material</th>
<th>Mechanical properties</th>
<th>Surface finishing</th>
</tr>
</thead>
<tbody>
<tr>
<td>SKD 11 (JIS) quenched</td>
<td>Hardness $H_v = 60$</td>
<td>Finished by lapling $R_{\text{max}} = 0.1 \mu m$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Work-place</th>
<th>Tensile strength: $\sigma = 79$ MPa</th>
<th>n-value: $h = 0.29$</th>
<th>Finished by cold rolling $R_{\text{max}} = 1 \mu m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ironing reduction</td>
<td>5, 20, 30 %</td>
<td>Die angle</td>
<td>10$^\circ$</td>
</tr>
<tr>
<td>Ironing travel</td>
<td>350 mm</td>
<td>Room temperature</td>
<td>20 + 5 $^\circ$ C</td>
</tr>
<tr>
<td>Ironing velocity</td>
<td>1 mm/s</td>
<td>Room humidity</td>
<td>45 + 5 %</td>
</tr>
</tbody>
</table>

[Fig. 2 Assembly drawing of main parts of the testing machine]
measured using lines scribed transversely on the workpiece at intervals of 5 mm. Assuming that the workpiece deforms under a plane strain condition of the width strain $\varepsilon_w = 0$, the expansion rate $\eta$ can be expressed as

$$\eta = \left(1 - \varepsilon_w\right) / \left(1 - \varepsilon_w\right) = r / (1 - r)$$

(1)

Where $r_0$ and $S_0$ are the surface areas of work metal, and $r_0$ and $t_0$ the thicknesses of work metal before and after ironing respectively, and $r$ the ironing reduction ($t_0 - t_1/t_0$). Fig. 3 shows the relation between $\eta$ and $r$. When the back-up plate with a grinding surface is used and a highly viscous mineral oil (stock-oil) is applied on both sides of the workpiece, the experimental points agree with a solid line described by the equation (1). On the other hand, when the file setting back-up plate is used and a highly viscous mineral oil is applied only on the die surface, the measured value of $\eta$ becomes slightly larger than the equation (1) and can be expressed approximately by the following empirical equation.

$$\eta = 1.2 r / (1 - 1.2 r) \quad (2)$$

The present experiments are carried out under the latter condition with ironing reductions 5, 20 and 30%. Therefore, the expansion rates of work metal $\eta$ corresponding to these reductions are 6.4, 31.5 and 56.3%, respectively.

The pressure acting on the die surface cannot be adjusted independently of other factors, because it may be influenced by the die angle, the ironing reduction, the frictional conditions on the die and the back-up plate and so on. The apparatus is devised to be able to change quickly the die as shown in Fig. 2, so as to facilitate mapping of the die surface and examination into effects of its material. The frictional surface of the die is finished by mapping for every test to the surface roughness $R_{max} = 0.1 \mu m$.

Lubricants used are five kinds of paraffinic mineral oil (PO1 - stock-oil) whose properties are shown in Table 2. Under the same conditions the tests are repeated five times in a room adjusted to constant temperature 20 °C and constant humidity 45%.

3. Variations of the frictional coefficient and frictional surface appearance during the ironing process

It has been confirmed from tests with various lubricants and reductions that variations of the frictional coefficient during the ironing process may be classified into four types as shown in Figs. 4 and Table 3, that is, I: Type with constant low friction, II: Type with friction increasing after constant low, III: Type with increasing friction and IV: Type with constant high friction.

Types I and II appear in high viscous mineral oils (stock-oil, PO4), Type III appears in moderate viscous mineral oils (P3,P2) and Type IV appears in low viscous mineral oils (PO1).

Corresponding with the variation types of the frictional coefficient, the surface appearances of work metal ironed also change in various types. Those are classified in six types from observation by the naked eye and a microscope, that is, A: rippling surface, B: abraded surface, C: scratched surface, D: gashed surface, E: micro-cracked surface and F: peeling surface. The surface appearance and the surface roughness curves in these types are shown in Figs. 5 - 10. In Fig. 4, the ironing travel when each type of the surface appearance is designated. Table 4 shows the frictional coefficient $\mu$ and the frictional shear stress $T$ for the ironing travel when each type appears.

![Fig. 3 Relation between ironing reduction and expansion ratio of work metal surface](image_url)

### Table 2 Paraffinic base oils

<table>
<thead>
<tr>
<th>Viscosity</th>
<th>PO1</th>
<th>PO2</th>
<th>PO3</th>
<th>PO4</th>
<th>PO5</th>
<th>St</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 °C</td>
<td>1.63</td>
<td>1.96</td>
<td>1.34</td>
<td>1.04</td>
<td>1.11</td>
<td>108</td>
</tr>
<tr>
<td>cst</td>
<td>1.43</td>
<td>1.10</td>
<td>1.11</td>
<td>1.00</td>
<td>1.11</td>
<td>111</td>
</tr>
<tr>
<td>98.5</td>
<td>0.68</td>
<td>0.64</td>
<td>0.54</td>
<td>0.50</td>
<td>0.55</td>
<td>59.5</td>
</tr>
<tr>
<td>Sulfur weight</td>
<td>0.02</td>
<td>0.01</td>
<td>0.10</td>
<td>0.13</td>
<td>0.18</td>
<td>71.5</td>
</tr>
<tr>
<td>Ring analysis</td>
<td>7.1</td>
<td>3.2</td>
<td>0.0</td>
<td>1.5</td>
<td>14.1</td>
<td>65.6</td>
</tr>
<tr>
<td>(n-d-M method)</td>
<td>62.6</td>
<td>69.1</td>
<td>63.2</td>
<td>67.2</td>
<td>65.6</td>
<td>787</td>
</tr>
<tr>
<td>Mean molecular weight</td>
<td>175</td>
<td>298</td>
<td>359</td>
<td>529</td>
<td>787</td>
<td>525</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Type</th>
<th>Lubricants</th>
<th>Ironing reduction</th>
<th>Frictional coefficient $\mu_0$</th>
<th>Frictional coefficient $\mu_{300}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>St, PO4</td>
<td>5</td>
<td>0.08 ± 0.12</td>
<td>0.09 ± 0.15</td>
</tr>
<tr>
<td>I</td>
<td>St, PO4</td>
<td>10</td>
<td>0.10 ± 0.12</td>
<td>0.11 ± 0.15</td>
</tr>
<tr>
<td>I</td>
<td>St, PO4</td>
<td>20</td>
<td>0.15 ± 0.12</td>
<td>0.14 ± 0.17</td>
</tr>
<tr>
<td>I</td>
<td>St, PO4</td>
<td>30</td>
<td>0.11 ± 0.12</td>
<td>0.14 ± 0.16</td>
</tr>
<tr>
<td>II</td>
<td>St, PO4</td>
<td>5</td>
<td>0.12 ± 0.12</td>
<td>0.20 ± 0.35</td>
</tr>
<tr>
<td>II</td>
<td>St, PO4</td>
<td>10</td>
<td>0.19 ± 0.12</td>
<td>0.25 ± 0.50</td>
</tr>
<tr>
<td>II</td>
<td>St, PO4</td>
<td>20</td>
<td>0.20 ± 0.12</td>
<td>0.25 ± 0.50</td>
</tr>
<tr>
<td>II</td>
<td>St, PO4</td>
<td>30</td>
<td>0.23 ± 0.12</td>
<td>0.25 ± 0.50</td>
</tr>
<tr>
<td>III</td>
<td>St, PO4</td>
<td>5</td>
<td>0.34 ± 0.12</td>
<td>0.45 ± 0.50</td>
</tr>
<tr>
<td>III</td>
<td>St, PO4</td>
<td>10</td>
<td>0.40 ± 0.12</td>
<td>0.46 ± 0.78</td>
</tr>
<tr>
<td>III</td>
<td>St, PO4</td>
<td>20</td>
<td>0.40 ± 0.12</td>
<td>0.46 ± 0.78</td>
</tr>
<tr>
<td>III</td>
<td>St, PO4</td>
<td>30</td>
<td>0.40 ± 0.12</td>
<td>0.46 ± 0.78</td>
</tr>
<tr>
<td>IV</td>
<td>PO1</td>
<td>5</td>
<td>0.60 ± 0.12</td>
<td>0.81 ± 0.83</td>
</tr>
<tr>
<td>IV</td>
<td>PO1</td>
<td>10</td>
<td>0.65 ± 0.12</td>
<td>0.82 ± 0.89</td>
</tr>
<tr>
<td>IV</td>
<td>PO1</td>
<td>20</td>
<td>0.65 ± 0.12</td>
<td>0.82 ± 0.89</td>
</tr>
<tr>
<td>IV</td>
<td>PO1</td>
<td>30</td>
<td>0.65 ± 0.12</td>
<td>0.82 ± 0.89</td>
</tr>
</tbody>
</table>

- I: Type with constant low friction, II: Type increasing after constant low friction, III: Type increasing friction, IV: Type with constant high friction.
3.1 Constant low friction type (I)

In the type (I), the frictional coefficient \( \mu \) is constant (0.08 \( \pm \) 0.15) throughout the ironing travel, and the "abraded surface" (Fig.6) appears except when the "rippling surface" (Fig.5) appears at the relatively high reduction 30\%. The "abraded surface" presented in Fig.6 shows a fine stripe-like effect in the ironing direction with surface roughness \( R_{\text{max}} \approx 0.5 \mu \text{m} \). In this case, the frictional surface of work metal in contact with the die seems to be in a boundary lubrication state because welding traces and micro pools which demonstrate the hydrodynamic effect cannot be observed. The "rippling surface" as shown in Fig.5 has directional asperities with surface roughness \( R_{\text{max}} \approx 2 \mu \text{m} \) and the wave length \( \lambda \approx 0.2 \sim 0.3 \text{ mm} \). These asperities seem to be produced due to plastic roughening phenomena under a relatively thick oil film.

3.2 Increasing friction after constant low friction type (II)

In the type (II), the "abraded surface" appears in the travel of constant low friction \( (\mu = 0.1) \), but when the frictional coefficient \( \mu \) increases beyond 0.13 the "scratched surface" shown in Fig.7(a) appears. When \( \mu \) exceeds 0.22, the "gouged surface" as shown in Fig.8(a) appears. The "scratched surface" occurs as the result of being ploughed by the metal transfer layer at the die exit which is observed as dark portions in Fig.7(b). Detailed discussions on the metal transfer layer were undertaken in the previous report (60/7). The "gouged surface" in Fig.8(a) has many cracks normal to the ironing direction, whose depth is about 15 \( \mu \text{m} \). It has been confirmed from minute observations that the cracks were produced by metal transfer to the die surface and peeling away from it (Fig.8(b)).

3.3 Increasing friction type (III)

In the type (III), a number of micro-cracks appear from the initial stage on the ironed surface as shown in Fig.9(a), and the number increases with an increase of \( \mu \). The micro-cracks are approximately normal to the ironing direction, and about 0.1 \( \sim \) 0.2 \( \mu \text{m} \) in length and 5 \( \sim \) 10 \( \mu \text{m} \) in depth; they are not distinguishable by the naked eye. On the other hand, micro-cracks have never been observed on the frictional surface of the work metal during ironing, which exhibits innumerable

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Table 4 Surface appearance of ironed work metal, and the frictional coefficient and the frictional shear stress during the ironing process

<table>
<thead>
<tr>
<th>Surface appearance</th>
<th>Frictional coefficient ( \mu )</th>
<th>Frictional shear stress ( \tau )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Rippling</td>
<td>0.08 ( \pm ) 0.10</td>
<td>15.7 ( \sim ) 19.6 ( \text{MPa} )</td>
</tr>
<tr>
<td>B: Abraded</td>
<td>0.10 ( \pm ) 0.15</td>
<td>19.6 ( \sim ) 29.4</td>
</tr>
<tr>
<td>C: Scratched</td>
<td>0.13 ( \pm ) 0.12</td>
<td>24.5 ( \sim ) 50.9</td>
</tr>
<tr>
<td>D: Gouged</td>
<td>0.22 ( \pm ) 0.64</td>
<td>37.2 ( \sim ) 78.4</td>
</tr>
<tr>
<td>E: Micro-cracked</td>
<td>0.51 ( \pm ) 0.98</td>
<td>68.6 ( \sim ) 96.0</td>
</tr>
<tr>
<td>F: Peeling</td>
<td>0.81 ( \pm ) 1.10</td>
<td>88.2 ( \sim ) 102.9</td>
</tr>
</tbody>
</table>

---

Fig. 4 Variations in frictional coefficient of paraffinic mineral oils during the ironing travel

![Diagram](image)

Lubricant : St, Reduction : 30\%
Ironing travel : 50 mm

Fig. 5 Ripping surface (A)

![Diagram](image)

Lubricant : St, Reduction : 5\%
Ironing travel : 100 mm

Fig. 6 Abraded surface (B)
merable fine spots with the surface roughness $R_{\text{max}} \approx 0.3 \mu m$ as shown in Fig. 9 (b). However, the frictional shear stress $\tau_m$ acting on the frictional surface is $68.5 \sim 96.0$ MPa as shown in Table 4 (E), which equals approximately the yield shear stress of the work metal. Therefore, the condition is deemed quasi-welding. The reason why the micro-cracks are produced seems to be a very severe shear deformation and a secondary tensile stress occurring near the die exit caused by the high frictional shear stress.

3.4 Constant high friction type (IV)

In the type (IV), the "peeling surface" as shown in Fig. 10(a) appears from the initial stage and deteriorates gradually in the ironing process. Clear surface cracks occur on the frictional surface of the work metal during ironing also, as shown in Fig. 10(a). The frictional shear stress $\tau_m$ is approximately equal (88.2 $\sim$ 102.9 MPa) to the yield shear stress of the work metal as shown in Table 4 (F). Therefore, the frictional surface seems to be under the welding condition.

Lubricant : St, Reduction : 30 %, Ironing travel : 300 mm

Fig. 7 Scratched surface (C)

Lubricant : P4, Reduction : 20 %
Ironing travel : 300 mm

Fig. 8 Gouged surface (D)

Lubricant : P2, Reduction : 20 %, Ironing travel : 300 mm

Fig. 9 Micro-cracked surface (E)
It is confirmed from detailed examinations of the vertical section of the work metal as shown in Fig.10(b) that the "peeling surface" occurs as follows. (a) A bulge occurs at the die inlet due to the high frictional resistance, and the work metal flows in beneath the bulge layer. As a result, an internal crack develops in the underlayer. (b) The formation of the internal crack and the drawing-in of the work metal surface alternate in the progress of the ironing process. In this way, straightform structures with a thickness of about 50 μm are produced as shown in Fig.10(b). (c) The surface layers peel off at the die exit due to the secondary tensile stress caused by the high frictional resistance and extinction of the die pressure there.

As mentioned above, the frictional surfaces of the work metal during ironing may be roughly classified into two regions, a boundary lubrication region and a welding region. The work metal surfaces after ironing are classified into the abovementioned six types. The wider the welding region becomes, the more the work metal surface after ironing deteriorates.

4. Assessment of anti-weldability

The frictional shear stress $\tau_m$ can be expressed by the equation (3), considering that the frictional surface consists of both the boundary lubrication region and the welding region.$^{[6],[7]}

$$\tau_m = \mu_b p_b (1 - \gamma_W) + \gamma_W \tau_W \quad \ldots \ldots \ldots (3)$$

Where $\gamma_W$ is the frictional coefficient at the boundary lubrication region, $p_b$ is the die pressure acting on the boundary lubrication region, $\gamma_W$ is the ratio of the welding region to the total contact area and $\tau_W$ is the frictional shear stress acting on the welding region. Figure 11 shows the relation between the frictional shear stress $\tau_m$ and the ratio of welding area to the total contact area $\gamma_W$. The values of $\gamma_W$ are measured using a profile projector. All the experimental points are approximately plotted on the linear line which is expressed by the least squares method as follows:

$$\tau_m = 72.1 \gamma_W + 23.9 \quad \ldots \ldots \ldots (4)$$

From the equations (3) and (4), $\tau_w = 98$ MPa and $\mu_b p_b = 23.9$ MPa are obtained. As mentioned above, this value of $\tau_m$ equals approximately the yield shear stress of the work metal 98.1 ~ 108.6 MPa, which may be presumed from the micro-Vickers hardness number $H_V = 45 \sim 52$ right under the welding region. Figure 12 shows the relation between the mean die pressure $p_m$ and the mean frictional shear stress $\tau_m$ at the die surface. It has been stated by Fukui et al.$^{[8]}$ that the more the frictional coefficient on the back-up plate exceeds that on the die during the ironing process, the higher the mean die pressure $p_m$ becomes. For this reason the mean die pressure $p_m$ increases with a lowering of the frictional shear stress.

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Equation (2)

$\mu_b = 0.15$

Equation (2)

$\mu_b = 0.10$

Equation (2)

$\mu_b = 0.02$

Equation (2)

$\mu_b = 0.01$

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Equation by the least squares method

$$\tau_m = -0.73 p_m + 167.3 \quad (5)$$

Equation by the least squares method

$$\tau_m = -0.73 p_m + 167.3 \quad (5)$$

Equation by the least squares method

$$\tau_m = -0.73 p_m + 167.3 \quad (5)$$

Equation by the least squares method

$$\tau_m = -0.73 p_m + 167.3 \quad (5)$$

Equation by the least squares method

$$\tau_m = -0.73 p_m + 167.3 \quad (5)$$

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Fig. 10 Peeling surface (P)

Fig. 11 Relation between the ratio of welding area and the frictional shear stress

Fig. 12 Relation between the contact pressure and the frictional shear stress
stress on the die side. The inverse-correlation between $t_m$ and $p_m$ shown in Fig. 12 can be expressed by the following empirical equation (5).

$$t_m = -0.73 \frac{p_m}{167.3} \quad \ldots \ldots \ldots (5)$$

Using the equations (4) and (5), the frictional coefficient $\mu = \frac{t_m}{p_m}$ is expressed as a function of the welding region ratio $\gamma_w$ only.

$$\mu = \frac{72.1 \gamma_w + 23.9}{-98 \gamma_w + 195.6} \quad \ldots \ldots \ldots \ldots \ldots (6)$$

When $\gamma_w$ equals zero in the above equation, $\mu = 0.152$. This is an appropriate value for the frictional coefficient $\mu_w$ under the boundary lubrication. Figure 13 shows the relation between $\gamma_w$ and $\mu$. The experimental points are quite consistent with the broken line expressed by the equation (6). In Figs. 11 and 13, two solid lines have been estimated, introducing into the equation (3) $\mu_w = 0.10$, $\gamma_w = 93.1$ MPa and $\mu_w = 0.15$, $\gamma_w = 102.9$ MPa respectively. All the experimental points fall within the range between the two solid lines.

The welding region $\gamma_w$ is a quantitative measure itself to assess the extent of the welding. $\gamma_w$ can be uniquely connected with $\gamma_w$ or $\mu$ by the equations (4) and (6) and also with the work metal surface appearances after ironing. Therefore, it can be concluded that the frictional coefficient $\mu$ itself represents the quantitative measure to assess the extent of the welding instead of $\gamma_w$.

From the $\mu$ - $h$ curves shown in Fig. 4, critical curves of $\mu = constant$ can be described on the $\eta$ - $h$ diagram, by giving the allowable surface of the work metal i.e., the allowable frictional coefficient $\mu$.

Figure 14 shows one example in the case where the "scratched surface" is regarded conveniently as allowable, namely, the allowable frictional coefficient $\mu$ is less than about 0.2. From this figure, the anti-weldability of the lubricants in the deformation processes can be clearly assessed. The low viscous mineral oils PO1 and P2 have virtually no anti-weldability against both the surface expansion $\eta$ and the sliding distance $h$. The anti-weldability of the mineral oil P4 is as good as that of the stock oil (St) for the sliding distance $h$. However, the anti-weldability of P4 against the surface expansion $\eta$ is inferior to that of St.

5. Conclusions

To establish methods to assess quantitatively the anti-weldability of lubricants in deformation processes, the strip-ironing type friction testing machine has been newly devised to augment the increasing ratio of the work metal surface $\eta$ and the ironing travel $h$, which greatly influences welding phenomena. It has been confirmed by the calibration of the measuring device and preliminary tests that this apparatus measures precisely without mutual interference the frictional force and the normal force, and can augment $\eta$ at least 60 % and $h$ to 350 mm. Using this apparatus, the paraffinic base mineral oils were tested with aluminum work metal (A 1050), and the following conclusions were made.

(2) Variations of the frictional coefficient $\mu$ during the ironing process are classified into four types; that is, I: constant low friction, II: increasing after low friction, III: increasing friction and IV: constant high friction. Corresponding with an increase of $\mu$ such as this, the surface appearances of the ironed work metals are classified into six types; that is, A: rippling surface, B: abraded surface, C: scratched surface, D: gouged surface, E: micro-cracked surface and P: peeling surface. The increasing process of $\mu$ was related to the occurrence and development of the welding.

(2) In the frictional surface of the work metal during ironing, only two regions of different lubrication states appear, that is, the boundary lubrication state...
and the welding state. Corresponding with the ratio of the welding region $\gamma_w$, the work metal ironed shows various surface appearances $A \sim F$ as mentioned above. Within the ranges of the present experiments, the frictional coefficient in the boundary lubrication state $\mu_p$ is about $0.10 \sim 0.15$ and the frictional shear stress acting on the welding region is about $93.1 \sim 102.9$ MPa, which approximately equals the yield shear stress of the work metal. Therefore, the frictional coefficient $\mu$ and the frictional shear stress $\tau_m$ are prescribed by a single valued function of the ratio of the welding region $\gamma_w$.

(3) On the basis of the above relation between $\mu$ or $\tau_m$ and $\gamma_w$, the frictional coefficients which can be measured precisely and easily are useful to assess the anti-weldability of the lubricants. Corresponding with the allowable surface appearance of the work metal, the critical curves of constant $\mu$ can be described on the $\eta - h$ diagram. It has been confirmed from this diagram that the high viscous mineral oil St shows an excellent anti-weldability against the surface expansion and the sliding distance, that the middle viscous oil Pb shows excellent anti-weldability for the sliding distance only, and that the low viscous oils PO1 and P2 show virtually no anti-weldability.

References