Measurement of Flow Stress by the Ring Compression Test*

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To measure the flow stress of metals under forming conditions, i.e. at large strains, high strain rates and elevated temperatures, a method based on the ring compression test is proposed. In this method, a ring-shaped specimen is compressed between two flat tools with and without lubrication. The coefficient of friction between the specimen and the tools is determined from the change in inner diameter, and then the load and reduction in height measured in the test are converted into the average flow stress and average equivalent strain by taking the friction into account. The calibration curves for determining the coefficient of friction, the average equivalent strain and the average flow stress are derived from the results of rigid-plastic finite element calculation. This method is simple to carry out and does not require control of friction during compression. Ring compression tests for certain kinds of lubricants, materials and strain rates are carried out. The method is confirmed to provide flow curves within an error of 5%, and is effective especially for measuring the flow stress of heat-resistant materials such as Ti alloys and Ni base superalloys which are formed at elevated temperatures. As an example, the flow curves of Ti-6Al-4V alloy measured by the proposed method are demonstrated.

** Key Words**: Plastic Forming, Finite Element Method, Friction, Measurement, Flow Stress, Ring Compression, Material Testing

1. Introduction

The recent trend in manufacturing requires the metal-forming industry to supply products with complicated shapes of high quality at low cost. To cope with this trend, computer simulations of deformation using the finite element method (FEM) have become of industrial importance. The use of appropriate flow stresses of metals under forming conditions is estimated to carry out accurate simulation.

The simple compression test is the most frequently used method to measure the flow stresses of metals. The method has been effectively used for estimating the flow stress at room temperature in the range of small strain and low strain rate. Repeated lubrication\(^{11}\) during a single compression is applied for measuring the flow stress at large strains. In general, it is difficult to apply the simple compression test to determine the flow stress under actual forming conditions, i.e. at high strain rates and elevated temperatures, because the effect of friction between the work piece and tools can hardly be eliminated. To solve the problem, the compression test with grooved dies\(^{10}\), called the constrained compression test, which is free from the effect of variations in frictional condition over the work-tool interfaces, was proposed by one of the authors. Using this method, the constrained compression test, flow stress-strain relations for various materials and forming conditions are easily collected under cold forging conditions. However, the required load to compress the specimen to a large reduction in height in the constrained compression test is several times as high as that in the simple compression test. Thus, the constrained compression test must be carried out on a machine with a large capacity. Since a heavy load causes a high pressure over the work-tool interfaces, the method should be applied after a sufficient consideration of decrease in the strength of the die, especially at elevated temperatures. Another problem associated with the applica-

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tion of the constrained compression test is the difficulty in making specimen from wires and thin plates. A method for measuring the flow stress of wire is established by compressing a wire to the radial direction(3).

At present, it is desired to develop effective methods for measuring the flow stress of Ti alloys and Ni base superalloys at elevated temperatures, especially above 1100 K. Compression tests at elevated temperatures must be carried out with appropriate lubricants over the specimen-tool interfaces to avoid diffusion bonding between the specimen and the tools. This fact suggests that the flow stress should be estimated in taking into account the effect of friction between the specimen and the tools.

The ring compression test(4)(7)(11) has been employed to measure the coefficient of friction and frictional shear stress. The testing method is applied for a height of specimen, strain rate and forming temperature. Recent reports(12)(13) describe the utilization of the method for measuring the coefficient of friction in forming of Ti alloy and Ni base superalloy at elevated temperatures.

In the present paper, a measuring method of flow stress-strain curves under forming conditions by the ring compression test is proposed. The basic concept of the method is that the measured load is transformed into flow stress by considering the coefficient of friction estimated from the change in inner diameter.

2. Development of Measuring Method

Deformation analyses of ring-shaped specimens are carried out for various parameters such as coefficient of friction, strain hardening exponent and strain rate-sensitive exponent related to the behavior of the specimen using the rigid-plastic finite element method(14), and then calibration curves providing the relations of the change in inner diameter, the average equivalent strain and the constraining factors with reduction in height for each parameter are prepared in advance. The flow curves can be determined from the changes in inner diameter (final diameter \(d_f\) initial diameter \(d_i\)) and compressive loads measured at each reduction in height in the ring compression tests with these calibration curves.

2.1 Analysis

In the analysis, a rigid-plastic material with the following flow curve is assumed:

\[
\sigma = a \cdot \varepsilon^n \cdot \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_0} \right)^m,
\]

where \(\sigma\) is the flow stress, \(\varepsilon\) is the equivalent strain, \(\dot{\varepsilon}\) is the strain rate, \(\dot{\varepsilon}_0\) is a standard strain rate (= 1) and \(a\) is a constant. The analysis of deformation is carried out for a specimen shape of outer diameter, inner diameter and height in the ratio of 6:3:2. Because of the symmetry of deformation, one-fourth of the cross section region of the ring-shaped specimen is divided into 77 elements. The calculation is repeated at a compression step of 2.8% to a maximum reduction in height of 70%. Figure 1 shows the deformation of a ring-shaped specimen, which is expressed by distortions of a grid drawn on the cross section, after compression under \(\mu = 0.15, \eta = 0\) and \(m = 0\). Generally, the deformation of a specimen is greatly affected by the coefficient of friction \(\mu\), and less significantly by the strain hardening exponent \(\eta\) and the strain rate-sensitive exponent \(m\).

2.2 Measurement of coefficient of friction

Figure 2 shows the change in inner diameter with reduction in height for each coefficient of friction when the strain hardening exponent \(\eta = 0\) and the strain rate-sensitive exponent \(m = 0\). The coefficient of friction may be determined accurately below \(\mu = 0.2\) because the change in inner diameter is sensitively affected by the coefficient of friction. Further increase in the coefficient of friction causes only a slight change in inner diameter, and thus, the estimation of the coefficient of friction becomes very difficult under poor lubricating conditions, especially when \(\mu\) is above 0.3. The effect of strain hardening exponent \(\eta\) and strain rate-sensitive exponent \(m\) on the inner diameter is shown in Table 1.
diameter is extremely small, as reported in the previous paper, and can be neglected at reductions in height of less than 40%. However, the $n$-value and the $m$-value should be considered at reductions in height above 40%. For an example, when $\mu$ is estimated to be 0.1 for $n=0.3$ at a reduction in height of 70%, the same inner diameter will lead to a coefficient of 0.09 for $n=0$ as can be seen from the calibration curves in Fig. 2 for $n=0$ and $m=0$. Thus, for this example, the curve in Fig. 2 provides a coefficient of friction of about 10% lower than the correct one. Similarly, Fig. 2 will cause an error of about 10% when applied to a method of $m=0.7$.

Since $n$-values of actual metals drop in the range of 0–0.5, the effect of $n$-value cannot be neglected if the flow curve is to be accurately determined. On the other hand, $m$-values are usually very small, e.g., 0–0.1 in cold forming and 0.1–0.2 in hot forming. Thus the effect of $m$-value may be neglected in most cases except for the superplastic state with $m$-values of greater than 0.3.

2.3 Calculation of average equivalent strain

The average equivalent strain $\bar{\varepsilon}_{eq}$ is given by substituting the equivalent strain $\dot{\varepsilon}_i$ calculated for each element into Eq. (2):

$$\bar{\varepsilon}_{eq} = \frac{\sum(\dot{\varepsilon}_i \times V_i)}{\sum V_i},$$

where $V_i$ is the volume for each element.

The average strain rate $\dot{\bar{\varepsilon}}_{eq}$ is also calculated using the strain rate $\dot{\varepsilon}_i$ obtained for each element from Eq. (3):

$$\dot{\bar{\varepsilon}}_{eq} = \frac{\sum(\dot{\varepsilon}_i \times V_i)}{\sum V_i}.$$  

In Fig. 3, the increase in average equivalent strain is shown against reductions in height for each coefficient of friction. The effect of the coefficient of friction on the average equivalent strain becomes significant as the height of the specimen decreases. The difference in the average equivalent strain between $\mu=0$ and 0.35 is about 0.34 at a reduction in height of 70%.

The effect of the strain hardening exponent and strain rate-sensitive exponent on the average equivalent strain is plotted in Fig. 4. The $n$-values (from 0 to 0.3) and $m$-values (from 0 to 0.7) do not affect the average equivalent strain.

2.4 Calculation of average flow stress

To determine the average flow stress from the measured load, the nominal compressive stress $p$ is defined as follows:

$$p = \frac{P}{A_0},$$

where $P$ is the compressive load and $A_0$ is the initial cross-sectional area of specimen, i.e., $A_0 = \pi(d_0^2 - d_i^2)/4$ for the specimen of outer diameter $d_0$ and inner diameter $d_i$.
The ratio of the nominal compressive stress $\bar{\sigma}$ to the average flow stress $\bar{\sigma}$ is defined as the constraining factor $f$:

$$f = \frac{\bar{\sigma}}{\bar{\sigma}}.$$  \hspace{1cm} (5)

The compressive load and the average flow stress are connected by the constraining factor with Eqs. (4) and (5). The measured load can be converted into the average flow stress when the constraining factor is calibrated quantitatively for every parameter.

In this paper, the constraining factor is calculated by substituting average equivalent strains $\bar{\varepsilon}_{\text{ave}}$ (Eq. (2)), average strain rates $\dot{\varepsilon}_{\text{ave}}$ (Eq. (3)) and compressive loads $P$ obtained from the finite element analysis into Eq. (6) derived from Eq. (5) by replacing $\bar{\sigma}$ with Eq. (1):

$$f = \frac{P}{A_0 \cdot \bar{\varepsilon}_{\text{ave}}^n} \left( \frac{\dot{\varepsilon}_0}{\bar{\varepsilon}_{\text{ave}}} \right)^n = \frac{P}{A_0} \cdot \frac{1}{\bar{\varepsilon}_{\text{ave}}^n} \left( \frac{\dot{\varepsilon}_0}{\bar{\varepsilon}_{\text{ave}}} \right)^n.$$  \hspace{1cm} (6)

The relation between the constraining factor and the reduction in height for each coefficient of friction under the same conditions of calculation as used in Fig. 3 is given in Fig. 5. The constraining factor does not vary so much by the change in coefficient of friction until the reduction in height approaches 40%. However, a remarkable increase in the constraining factor appears at reductions in height above 40% for large coefficient of friction and the difference due to the coefficient of friction becomes significant. A constraining factor for coefficient of friction $\mu=0.3$ is four times as large as one for $\mu=0$ at a reduction in height of 70%.

The variation in constraining factor with the strain hardening exponent $n$ and the strain rate-sensitive exponent $m$ is examined under $\mu=0.1$ in Fig. 6. The constraining factor is independent of the $n$-value and the $m$-value. The trend coincides with that of the average equivalent strain.

Practical assessment of an average flow stress $\bar{\sigma}_{\text{ave}}$ at each reduction in height is carried out by Eq. (7) with a measured load $P_m$ and a constraining factor $f$ given in Figs. 5 and 6:

$$\bar{\sigma}_{\text{ave}} = \frac{P_m}{A_0 \cdot f}. \hspace{1cm} (7)$$

### 2.5 Determination of flow curve

Flow curves for materials can be approximately determined according to the following procedure. First, an inner diameter of a ring-shaped specimen is measured at each reduction in height, then a coefficient of friction corresponding to the change in inner diameter is approximated from Fig. 2. By using the coefficient of friction obtained, an average equivalent strain and a constraining factor for each reduction in height are estimated from Figs. 3 and 5, respectively. An average flow stress is calculated by substituting the constraining factor into Eq. (7). The flow curve, obtained as a combination of the average equivalent strain and the average flow stress at each reduction in height, might not be of sufficient accuracy to be applied to the analysis of deformation because the effects of $n$- and $m$-values are not included.

To measure the flow stress more exactly, the effect of the $n$-value on the flow stress is considered. The coefficient of friction calculated by assuming $n=0$ and $m=0$ is modified by the use of the new relations between the inner diameter and the coefficient of friction for the $n$-value of the newly obtained flow curve. Next, the constraining factor and the average equivalent strain are renewed by using the renewed coefficient of friction. This procedure to determine the flow curve is repeated until the flow stress converges. The method for determining the flow curve is summarized in Fig. 7. In general, the coefficient of friction and the flow stress become steady after 2 iterations of calculation. The deviation of flow stress obtained by the first approximation from the critical flow stress is

![Fig. 5](image1.png)

**Fig. 5** Variation in constraining factor with reduction in height for coefficient of friction from 0 to 0.3

![Fig. 6](image2.png)

**Fig. 6** Effect of strain hardening exponent $n$ and strain rate-sensitive exponent $m$ on constraining factor ($\mu=0.1$)
within 1 to 3%.

The effect of $m$-value on the flow stress is neglected in the present process because it is impossible to estimate the $m$-value from only one ring compression test.

3. Experiment

To evaluate the flow curves estimated from ring compression tests, uniform compression tests are carried out under the same testing conditions.

3.1 Testing apparatus

In Fig. 8, the common testing apparatus used in both the ring compression and the uniform compression tests is illustrated. The ring-shaped and the cylindrical specimens are compressed between two flat dies with smooth surfaces and slowly compressed through the subpress by a 100-tonf compression testing machine. The compressive load is measured by a load cell located on the upper platen of the subpress.

3.2 Testing method

(1) Ring compression test The ring compression tests are carried out for five materials shown in Table 1 under three conditions of lubrication; with no lubricant, machine oil and a P.T.F.E. (Teflon) sheet with vaseline over the specimen-die interfaces. Specimens are 16 mm in outer diameter, 8 mm in inner diameter and 5.3 mm high for pure copper of C1100 and aluminum alloy of A5052, and 15 mm in outer diameter, 7.5 mm in inner diameter and 5 mm high for steel alloys of S45C, SCM435 and SCR420. The end surfaces of specimens used are finished to less than 0.6 µm $R_{max}$ in roughness. To avoid variation in friction during compression, the machine oil and the P.T.F.E. sheet with vaseline are renewed at every reduction in height of 10% and 5%, respectively. The compressive load and the change in inner diameter of specimen are measured at every reduction in height of 10%.

(2) Uniform compression tests The uniform compression tests are executed for the same materials as used in the ring compression tests and the results are compared with those of the ring compression tests. The specimens are formed into a cylinder of 16 mm in diameter and 24 mm in height with a surface smoother than 0.6 µm $R_{max}$ in roughness. The P.T.F.E. sheet with vaseline reduces the friction between the specimen and the dies. The lubricant is changed at every 5% height reduction to keep the friction constant. The compressive load is also recorded at the same compression step. The flow curve can be calculated from the relation between the compressive load and the reduction in height.

![Flow curve for compressed material](image)

Table 1 Materials used in compression tests

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Copper</td>
<td>500°C 90min F.C.</td>
</tr>
<tr>
<td>Aluminum Alloy</td>
<td>400°C 120min F.C.</td>
</tr>
<tr>
<td>A5052</td>
<td></td>
</tr>
<tr>
<td>S45C</td>
<td>As Received</td>
</tr>
<tr>
<td>SCM435</td>
<td>As Received</td>
</tr>
<tr>
<td>SCR420</td>
<td>As Received</td>
</tr>
</tbody>
</table>

Fig. 7 Procedure to determine flow curve for compressed material

Fig. 8 Testing apparatus
3.3 Experimental results and discussion

The variations in inner diameter with the reduction in height in the ring compression tests for pure copper with no lubricant and for A5052 with machine oil are plotted on the calibration curves at the same time in Fig. 9. The coefficients of friction are estimated to be nearly equal to 0.15 and 0.05 for no lubricant and machine oil, respectively.

In Fig. 10, the flow curves estimated by the ring compression test are compared with those obtained by the uniform compression test for certain kinds of materials. The ring compression test provides comparatively exact flow stresses whose deviations from the flow stress measured by the uniform compression test are within 5% in the range tested.

Figure 11 shows the flow curves measured under various conditions of lubrication by the ring compression test. The effect of the lubricating condition on the flow estimated stress is small in the ring compression test and the maximum deviation from the flow stress specified by the uniform compression test is 4%. These results indicate that the flow stress for material can be precisely measured using the present method irrespective of the frictional condition between the specimen and the dies, which has not been achieved in previous flow stress measurements.

Thus, since the flow stress is estimated without controlling the friction between the specimen and the dies in the present method, no specially designed dies are required. Another advantage of this method is that it is possible to measure the flow stress with using a special lubricant or method of lubrication.

The next application of the present method is to the high velocity compression. The ring compression test with P.T.F.E. sheets and vaseline as a lubricant is carried out for an aluminum alloy specimen of A5052 on a crank press with a capacity of 30 ton which provides a high strain rate. In Fig. 12, the flow curve at a strain rate of about 5.0 s⁻¹ in the ring compression test is shown and compared with that in the uniform compression test.
high velocity compression test without barreling which is executed according to the same testing procedure as used in the compression at a low strain rate. The flow stress obtained from the ring compression test agrees with that from the uniform compression test within a 1% error. The result suggests the feasibility of the method for measuring the flow stress with a high accuracy up to comparatively high strain rates using the present method.

The flow curves measured at elevated temperatures, 1101, 1180 and 1196K for Ti-6Al-4V (6%Al, 4% V), which is not specially treated to arrange the grain size, are shown in Fig. 13. The flow stress is kept nearly constant against the equivalent strain, but it is sensitive to temperature.

4. Conclusions

A method to estimate the flow curves from the compressive load and the inner diameter at each reduction in height measured in the ring compression test is proposed. The constraining factor and the average equivalent strain at each reduction in height are calculated by using the rigid-plastic finite element method, and are used to convert the measured load, reduction in height and final inner diameter to a flow curve.

The proposed method is applied to the estimation of flow stress under various conditions of lubrication, material and strain rate. It is clarified that the flow stresses assessed using the present method agree with those obtained by the uniform compression test within an error of 5%. These results suggest that the present method is effective in measuring the flow stress at elevated temperatures with appropriate lubricants.

References


