Influence of Friction and Plastic Anisotropy in Cube- and Ring-Compression Test*

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Abstract
An extruded or rolled material such as a bar and a tube naturally possesses plastic anisotropy like a sheet. The property influences the metal flow in bulk forming as well as in sheet metal forming. In this paper, some examples of the anisotropic bulk deformations in a cube- and a ring-compression test were demonstrated. The cube with the edges of 1 mm long, which was cut out of a round bar or a tube, was compressed in z-axis under a well-lubricated condition by applying beef-tallow. After the compression test, the strain ratios of $\varepsilon_y$ to $\varepsilon_x$ were 0.83 and 0.76 for A1050 and A6063 respectively. They showed normal anisotropy, because the ratios of $\varepsilon_y/\varepsilon_x$ keep unity if they are isotropic materials. Furthermore, friction also affects the metal flow for the anisotropic material. The ratios of $\varepsilon_y/\varepsilon_x$ changed when the cubes were compressed under different frictional conditions by using some lubricants such as beef-tallow, VG460, VG100, castor oil, and no lubrication. The anisotropic deformation was restrained by the higher-frictional die-surface. Also the ring-compression test, as another example, was investigated, which is a well-established test to determine the friction coefficients by measuring the change in the inner diameter. Plastic anisotropy and friction influenced the reduction in the inner diameter, so the coefficient of friction must be decided with appropriate diagrams that consider the plastic anisotropy of the material.

Key words: Plastic Anisotropy, Friction, Lubrication, Metal Forming, Forging

1. Introduction

In cold forging, the working pressure is so high due to high yield stress of material, the hydrostatic stress generated by constraint of metal flow, the redundant work, and friction. Decreasing the pressure and the load positively affects the accuracy of products and the die life. They have been improved by innovations of the technologies such as CAE/CAM, die making, die material and coating, quality of work material, high-precision pressing machine, lubrication, etc. Especially the CA technologies make rapid progress, which are indispensable to the design of the die and process. Constructing more practical data-bases on friction and mechanical properties of materials would improve estimation by the numerical simulation for precision forging.

For sheet metal forming a material property of plastic anisotropy is an important issue to predict forming shape, yield stress, and forming limits. However, the bulky materials such as a round bar and a tube for forging and tube-forming will show the plastic anisotropy. The character may vary the material flow, which also will affect the final accuracy of forging products. Pöhlandt et al. have proposed concepts for characterizing...
plastic anisotropy of materials such as round bars, wires, and tubes\(^{(3)}\). Bjorn Carlsson et al. have described a practical method of determining material coefficients in Hill's quadratic yield criterion for a thin wire using a lateral compression test\(^{(4)}\). Having discussed independently some experimental results\(^{(5)}\) about compression tests for an extruded bar and tube, we have improved the determination of Hill's constants\(^{(6),(7)}\).

Friction also influences the material flow. This concept is applied to measurement of friction. For example, the ring-compression test is a well-established method to measure the friction between a die and a material in forging. The different conditions of lubrication or friction sensitively influence deformation of the inner diameter of the ring. The influences of plastic anisotropy and friction on the deformation in the test have been reported\(^{(8),(9)}\).

Moreover when plastic anisotropy of a material should not be ignored, an important notice of using the conventional calibration diagrams, which are based on isotropic properties, was presented by the authors\(^{(5)}\) and P. Huml et al.\(^{(10)}\).

This paper presents the various deformations in a cube- and a ring-compression test under different lubrication conditions. The cubes of 99.5% Al and Al-Mg-Si alloy were cut out of an extruded tube and bar respectively. When the cubes were compressed, each shape was different from that of the compressed cube of isotropic material. Furthermore the anisotropic deformation was strongly restrained by a higher-frictional die-surface. Also the yield criterion for a thin wire using a lateral compression test\(^{(4)}\). Having discussed the flow rules are used as

\[
de \varepsilon_y = \frac{d \lambda}{\partial f (\sigma_y)/ \partial \sigma_y}.
\]

Substituting Eq. (2) into Eq. (3) gives,

\[
de \varepsilon_r = \frac{d \lambda}{\partial f (\sigma_r)/ \partial \sigma_r} \left\{ -2G (\sigma_r - \sigma_t) + 2H (\sigma_r - \sigma_\theta) \right\} \tag{4a}
\]

\[
de \varepsilon_\theta = \frac{d \lambda}{\partial f (\sigma_\theta)/ \partial \sigma_\theta} \left\{ 2F (\sigma_\theta - \sigma_t) - 2H (\sigma_\theta - \sigma_\theta) \right\} \tag{4b}
\]

\[
de \varepsilon_z = \frac{d \lambda}{\partial f (\sigma_z)/ \partial \sigma_z} \left\{ -2F (\sigma_z - \sigma_t) + 2G (\sigma_z - \sigma_\theta) \right\}. \tag{4c}
\]

For the z-directional uniaxial stress condition the state as \(\sigma_r=\sigma_\theta=0\) can be given,

\[
de \varepsilon_z/d \varepsilon_r = F/G \tag{5a}
\]

is derived from the Eqs. (4a) and (4b). Similarly supposing \(\sigma_\theta=\sigma_r=0\) for the r-directional uniaxial stress condition and \(\sigma_r=\sigma_\theta=0\) for the \(\theta\)-directional uniaxial stress condition,

\[
de \varepsilon_r/d \varepsilon_\theta = G/H \tag{5b}
\]

\[
de \varepsilon_\theta/d \varepsilon_z = F/H \tag{5c}
\]

are derived respectively. These equations (5a)-(5c) provide simple relations between the incremental strains and the constants of plastic anisotropy. As the constant of \(H\) is independent of the equivalent strain, it can be acceptable that \(H=1\) for universality. So \(F\) and \(G\) are determined as

2. Determining anisotropy constants

2.1 Hill's quadratic yield criterion

Hill's quadratic yield criterion was proposed in 1948\(^{(11)}\), which is simple to generalize the von-Mises criterion of the plastic anisotropy materials. It has the form

\[
2f(\sigma_0) = F(\sigma_r - \sigma_t)^2 + G(\sigma_r - \sigma_\theta)^2 + H(\sigma_\theta - \sigma_t)^2 + 2M(\tau_\theta)^2 + 2N(\tau_\phi)^2 = 2C^2 \tag{1}
\]

where \(F, G, H, L, M,\) and \(N\) in Hill's quadratic yield criterion\(^{(11)}\) were determined roughly by the results of good lubrication\(^{(3)}\). They were used for the FEM-analysis to draw the calibration diagrams of the ring-compression test for the plastic anisotropic material. Plastic anisotropy as well as the friction influenced the deformation of the ring.
\[ F = \frac{d\varepsilon_z}{d\varepsilon_r} \quad (6a) \]
\[ G = \frac{d\varepsilon_z}{d\varepsilon_\theta}. \quad (6b) \]

2.2 Small-cube-compression test

Hill's constants are measured under the uniaxial stress condition in the \( r \)-, \( \theta \)-, and \( z \)-direction. If the bar material is isotropy, the \( z \)-directional tensile test is used to realize the uniaxial stress condition. However the tensile test is usually difficult to carry out in the \( r \)- or \( \theta \)-direction. And in the \( z \)-directional uniaxial tension test, the stresses of \( \sigma_r \) and \( \sigma_\theta \) are not zero when the material has plastic anisotropy\(^5\). In this paper we use a small-cube-compression test\(^6\) to determine Hill's constants, \( F \), \( G \), \( H \), \( L \), \( M \), and \( N \).

Figure 1 illustrates a position of the small-cube and a direction of compression. Each plane of the cube has the normal directions to coincide with the \( r \)-, \( \theta \)-, and \( z \)-direction. When the small-cube is compressed under a well-lubricated condition, nearly uniaxial compression is postulated. For example in the \( r \)-directional compression, the \( \theta \) and \( Z \)-surfaces are free. Therefore we can set \( \sigma_\theta \) and \( \sigma_z \) equal to zero. To determine Hill's constants \( F \) and \( G \), it is necessary to compress in the two directions selected from the \( r \)-, \( \theta \)-, and \( z \)-directions.

Additionally Hill's constants \( L \), \( M \), and \( N \) are calculated by the same procedure as the use of Lankford value on the sheet metal forming. Figure 1(b)-(d) illustrate the rotation of cubes and the direction of compression. The small cube is cut out of an original bar, which has the rotated axis on each plane at an angle of \( \alpha \) degrees. The values of \( Z_\alpha \) have been defined on the axial-plane or \( Z \)-plane as a strain ratio of a width-strain to the axial-strain, or \( Z_\alpha = \varepsilon_w / \varepsilon_z \), where the width-axis is perpendicular to both of the directions of the compression and the axial. Substituting 0-, 45-, and 90-degrees into \( \alpha \), we can obtain the following relations.

\[ Z_0 = \frac{H}{G} \quad (7a) \]
\[ Z_{45} = \frac{(2N - F - G)}{2(F + G)} \quad (7b) \]
\[ Z_{90} = \frac{H}{F}. \quad (7c) \]
Similarly other values of $R_\alpha$ and $\Theta_\alpha$ are defined\(^7\). The Hill’s constants ratios are determined as follows:

\[
F = \frac{1}{Z_{90}} \quad (8a)
\]
\[
G = \frac{1}{Z_0} \quad (8b)
\]
\[
\frac{L}{F} = \frac{(R_{45}+0.5)(1/R_0+1/R_{90})}{(R_{45}+0.5)(1/R_0+1/R_{90})} \quad (8c)
\]
\[
\frac{M}{G} = \frac{(\Theta_{45}+0.5)(1/\Theta_0+1/\Theta_{90})}{(\Theta_{45}+0.5)(1/\Theta_0+1/\Theta_{90})} \quad (8d)
\]
\[
N = \frac{(Z_{45}+0.5)(1/Z_0+1/Z_{90})}{(Z_{45}+0.5)(1/Z_0+1/Z_{90})}. \quad (8e)
\]

3. Influence of friction and anisotropy

3.1 Testing materials and lubrication

Table 1 shows two materials of A1050-F (tube) and A6063-T1 (bar) that are used for the small-cube-compression test. In the ring-compression test to estimate the coefficient of friction, A6063-T1 (bar) is used. The material of A1050-F is 99.5% aluminum as fabricated, which is an extruded tube with 17.8 mm in outer diameter and 1.3 mm in thickness. A6063-T1 (bar) is aluminum alloy containing 0.5% Mg and 0.39% Si to be heat-treated for natural-age-hardening, which is an extruded round bar 16.5 mm in diameter. The specimens are cut out with an electrical-discharged wire.

Table 2 shows the lubricants for the small-cube-compression test and the ring-compression test. Beef-tallow, $B$, is an animal fat with good performance for lubrication. The symbol $BG$ stands for beef-tallow and graphite powder with about 10 $\mu$m in mean diameter. VG100 and VG460 are pure paraffin mineral oil, which has low viscosity of 100 mm$^2$/s and high viscosity of 460 mm$^2$/s. Castor oil is a vegetable oil. The symbol $D$ indicates almost dry condition or a poorly lubricated condition for high friction. In other words, some specimens are degreased with acetone by using ultrasonic cleaning.

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Materials for small-cube- and ring-compression test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbols</td>
<td>Aluminum tube and Al-alloy bar</td>
</tr>
<tr>
<td>A1050-F</td>
<td>99.5% Al fabricated. Tube (outer dia. φ17.8 mm, thickness 1.3 mm)</td>
</tr>
<tr>
<td>A6063-T1</td>
<td>A-alloy (Mg 0.50, Si 0.39 mass%) natural age hardening Round bar ( φ16.5 mm)</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Table 2</th>
<th>Lubricants for small-cube- and ring-compression test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symbols</td>
<td>Contents of lubricants and degreasing</td>
</tr>
<tr>
<td>$B$</td>
<td>Beef-tallow</td>
</tr>
<tr>
<td>$BG$</td>
<td>Beef-tallow 60% and graphite powder 40%</td>
</tr>
<tr>
<td>$L$</td>
<td>Mineral oil, 100 mm$^2$/s at 40 degrees C</td>
</tr>
<tr>
<td>$H$</td>
<td>Mineral oil, 460 mm$^2$/s at 40 degrees C</td>
</tr>
<tr>
<td>$C$</td>
<td>Castor oil</td>
</tr>
<tr>
<td>$D$</td>
<td>Degreased with acetone</td>
</tr>
</tbody>
</table>
3.2 Small-cube-compression test

The cube specimens with edges of 1 mm long are compressed to about 50% reduction in height under various friction conditions by using the different lubricants shown in Table 2. The cubes are cut out of a bar at a radius, \( a \), of 6.5 mm. A worm-gear-jack press machine with a velocity of 0.1 mm/s is used to compress the cubes. The die material is tool-steel for cold forming, SKD11 in JIS, with hardness of 786 HV after quenched and tempered, which has the surface roughness of 0.8 \( \mu \)m in Rz.

Figure 2 shows the typical upper surfaces after the cubic specimens are compressed in the radial direction, using two lubricants of \( BG \), VG100, and poor lubrication by being degreased with acetone. A white square frame is shown as an initial outline of the upper surface of the cube before compression. A cube of an isotropic material always keeps the cross section of square during the compression under well-lubricated condition. However the upper surface lubricated with \( BG \) was rectangular rather than a perfect square, which has an axial edge with 1.617 mm long and a circumferential edge with 1.216 mm long from the initial edges of 0.995 and 0.999 mm, respectively. So the strain ratio of \( \varepsilon_z \) to \( \varepsilon_\theta \) is calculated to be 2.5 from the changing length of the sides. Another cube lubricated with VG100 shows the strain ratio, \( \varepsilon_z / \varepsilon_\theta = 1.8 \), also the cube degreased with acetone shows the strain ratio, \( \varepsilon_z / \varepsilon_\theta = 1.4 \). The \( BG \)-lubricated specimen gives a larger ratio of \( \varepsilon_z \) to \( \varepsilon_\theta \) than the VG100-lubricated one. Then the VG100-lubricated one shows a larger ratio than the poorly lubricated one in the ratio of \( \varepsilon_z / \varepsilon_\theta \).

Figure 3 shows the surface-profiles of the upper-side of the compressed specimen. Generally, in upsetting, lubricant is applied by a squeeze action between a die and a material. The \( BG \)-lubricated surface has deep valleys on the profile which was generated by roughening freely with a small area. A thick oil-film may be formed at the interface. On the VG100-lubricated surface, the depth of the valleys decrease and several peaks on the profile are flatted. Also a large number of the fine secondary oil-pits are observed on the flatted local area. The condition of poor lubrication by degreasing with acetone develops into a larger flattened area than the other lubricated condition, but it does not become perfectly smooth. Some large valleys remain still when the reduction in height is only 50% in the compression test. The maximum values of the surface roughness of \( BG \), VG100, and \( D \) are about 8, 5, and 4 \( \mu \)m respectively. A larger amount of lubricant may be held and can be lubricated between the die and the material. The quantity of \( BG \) is larger than that of VG100, so it can be found that \( BG \) keeps a better-lubrication condition than VG100 during compression.

As freely roughened peaks of the profile were flatted by the smooth die, the area under the envelope of the profile curves in Fig.3 is almost equivalent to the volume of oil film. Accordingly a mean thickness of oil film is estimated by dividing the area by the length of side in the z-direction, which means nominal mean oil-film thickness.

Fig.2  Upper of surfaces after compressing cubic Al-alloy, A6061-T1, in radial direction under different lubrications and also squares with white lines indicating initial outlines cross section.
Fig. 3  Surface-profiles of compressed under surfaces as shown in Fig. 2

Fig. 4  Relationship between mean depth of valleys on surface-profiles and strain ratio of $\varepsilon_z$ to $\varepsilon_\theta$

Fig. 5  Mean pressure and strain ratios in small-cube-compression test under different lubrications
Figure 4 shows the relationship between the mean depth of the valleys on the surface-profiles and the strain ratio of $\varepsilon_z/\varepsilon_{\theta}$. As the lubricant of $B$ and $BG$ are semi-solid or mixed with solid, a larger amount of lubricant is kept than liquid lubricant such as VG100, VG460, and Castor oil. These oils show a small difference in the mean depth of valleys. In this test the die approaches the material slowly, so any oil tends to squeeze out from the interface. When the specimen is degreased with acetone, there are justly no lubricants on the surface profile. The nominal oil film thickness is rightly insignificant for degreasing the specimen with acetone, so it may be better that the point of $D$ is plotted again at the nominal mean oil-film thickness of zero. When the mean depth of the valleys decreases, the strain ratio of $\varepsilon_z/\varepsilon_{\theta}$ also tends to decrease.

Figure 5 illustrates two examples of the relationship between mean compression pressure and strain ratios. The load is divided by a final area after compression to calculate the mean pressure. The strain ratios are plainly related with anisotropy under no friction condition according to Eqs.(5a)-(5c). In Fig.5(a), which is an example of A6063-T1 (bar), the strain ratio of $\varepsilon_z$ to $\varepsilon_{\theta}$ indicates 2.5 for the mean pressure of 240 MPa. The strain ratio $\varepsilon_z/\varepsilon_{\theta}$ decreases as the mean pressure rises. Meanwhile the other strain ratios of $\varepsilon_z/\varepsilon_r$ and $\varepsilon_r/\varepsilon_z$ tend to increase slightly as the mean pressure increases. These tendencies are similar to those of A1050-F (tube) as shown in Fig.5(b), namely the strain ratio $\varepsilon_z/\varepsilon_{\theta}$ is shown about 3.0 for the mean pressure of 130 MPa, which decreases as the mean pressure rises. The other strain ratios of $\varepsilon_z/\varepsilon_r$ and $\varepsilon_r/\varepsilon_z$ tend to increase slightly as the mean pressure increases.

Judging from both Figs.4 and 5, we find that the lower mean pressure results in lower friction. If these strains such as $\varepsilon_z$, $\varepsilon_{\theta}$, and $\varepsilon_r$ are restricted by a die-surface with the higher friction, the incremental strain of the material near the die surface can not develop. Therefore the strain ratio approaches unity. Conversely the material with plastic anisotropy can flow uniformly in its own preferred direction without the strong restriction by higher friction.

Figure 6 shows the typical upper view of the specimen which was compressed without lubrication in the radial direction by 50% reduction in height. In Fig.6 the white frame 0.998 mm x 1.000 mm indicates the initial shape of the upper surface. After the compression, the upper and lower surfaces became rectangular. The central cross-section was deformed to nearly rectangular with barreling. So we averaged lengths in $z$ direction on the upper surface, the lower surface, and the central cross-section to obtain 1.487 mm, similarly we obtained 1.339 mm in $\theta$ direction. Consequently the strain ratio resulted in $\varepsilon_z/\varepsilon_{\theta}=\ln(1.487/0.998)/\ln(1.339/1.000)=0.398/0.292=1.4$. So we found $G/H=\varepsilon_z/\varepsilon_{\theta}=1.4$ which also showed anisotropy under a high frictional condition.

![Fig.6 Upper view of specimen compressed by 50% without lubricants after rinsing with acetone, which has white square frame indicating initial shape](image-url)
Figure 7 shows the numerical simulation of the small-cube-compression test by 50% reduction in height using a commercial code of FEM, ANSYS-University-Introductory which considered plastic anisotropy with Hill's constants. We determined that the values of Hill's constants $F$, $G$, $H$, $L$, $M$, and $N$ were respectively 2.3, 2.5, 1.0, 3.4, 2.5, and 4.5 of the material(7) using the cube-compression test under a well-lubricated condition and Eqs.(8a) - (8e). As low friction applied to the die surfaces, the constants were incorrect strictly. Supposing the constants are roughly effective in this paper, we could use them for the FEM. Figure 7 is shown as a 1/8-model to be constructed with the elements of 20 by 20 by 20. Coulomb's friction coefficient $\mu$ of 0.3 was estimated by the ring-compression test to be mentioned later. The length of the edge and holding the initial franc surface corresponds to the experimental shape of Fig.6.

3.3 Ring-compression test

The anisotropic material affected the metal flow of the small-cube-compression test. In the ring-compression test, the plastic anisotropy also influences the metal flow like friction(5). Considering the influences of $F$ and $G$, ideal anisotropy $F : G : H : M = 2 : 1 : 1 : 3$ and $F : G : H : M = 1 : 2 : 1 : 3$ are assumed.

Figure 8(a) shows the calibration curves to estimate Coulomb's coefficient of friction from the ring-compression test, which includes the result calculated for two types of material with isotropy and anisotropy by a commercial code of FEM, ANSYS-ED ver. 9.0. The original geometry of a ring specimen has height : inner diameter : outer diameter proportions of 1:2:4. And the FEM-calculation conditions are axial symmetry model by using the ring elements of 20 by 40 and the contacting elements of 66.

Hill's constants of $F$ and $G$ directly affect the ring deformation. When the ring material has anisotropy of $F/G=0.5$, the inner diameter is smaller than that of isotropy in the ring-compression test. Conversely when the ring material has anisotropy of $F/G=2$, the inner diameter is larger than that of a material of isotropy.

Under a frictionless condition, any point of a material in the ring flow towards outer side from the center like a solid billet. Meanwhile when the ring material has anisotropy as $F < G$ or $\varepsilon_\theta < \varepsilon_r$, enlargement of the radial width becomes larger than the circumferential elongation. Thus an inner material tends to flow towards the central direction. As a result, the inner diameter becomes smaller than predicted when isotropy is assumed. Conversely when the material has anisotropy of $F > G$ or $\varepsilon_\theta > \varepsilon_r$, the circumferential elongation...
becomes larger than the radial width enlargement. Thus an inner material tends to flow towards the outer direction, so the inner diameter becomes larger than that to be predicted under supposed isotropy.

As high friction restricts to the natural flow of material, the reduction in the inner diameter is not largely different under the high-frictional condition of $\mu=0.3$. However it is difficult to estimate how the material flows under frictional conditions because there are distributions of the circumferential stress and the radial stress.

Here, we show the calibration diagram for a material A6063-T1 as an example. The ring has an outer diameter of $\phi 10$ mm, an inner diameter of $\phi 5$ mm, with a height of 2.5 mm, which was normally machined out of the $\phi 16.5$-mm bar. Hill’s anisotropic constants of the A6063-T1 (bar) are determined from the small-cube-compression test by using Eqs.(8a)-(8e). The cubes with edges of 2.5 mm long are cut out of the bar at $a=3.75$ mm. The strain ratios show $Z_0=0.34$, $Z_{60}/Z_0=0.37$, $\Theta_0=1.1$, and $\Theta_{45}=1.1$ or Hill’s constants show $F : G : H : M = 2.7 : 2.9 : 1 : 2.8$). The ring specimen is compressed to about 40-50% reduction in height with a compressing velocity of 0.1 mm/s. The dies conditions were the same as they were used for the small-cube-compression test. The each specimen was lubricated with beef tallow ($B$), beef tallow + graphite ($BG$), VG100 ($L$), and no lubricants after being rinsed with acetone ($D$).

**Fig.8** Different diagrams of ring-compression test to determine friction for materials of isotropy and plastic anisotropy.
Figure 8(b) shows the testing results and calibration curves for an isotopic material. The lubricants B and BG are better than L to reduce friction (Fig.9). Naturally degreasing with acetone shows the highest friction. The lubricants B and BG indicate \( \mu \) of 0.05. Similarly \( \mu \) of 0.07 and 0.2 are found for L and D respectively.

While an appropriate diagram for plastic anisotropy, Fig.8(c), is referred, B, BG, L, and D show \( \mu \) of 0.08, 0.08, 0.1, and 0.3 respectively. Consequently, plastic anisotropy and friction also influence the material flow in the ring-compression test. So we have to note that the appropriate diagrams should be used for a material with strong plastic anisotropy in the ring-compression test.

**Conclusions**

We have tried to determine roughly and practically Hill's anisotropy constants of a bar and a tube in Hill's quadratic yield criterion by simple small-cube-compression tests under better lubrication with beef-tallow or beef-tallow + graphite. Using these material constants, we have modified the diagrams of the ring-compression test. We would like to sum up the results of our investigation of the influence of friction and plastic anisotropy on the metal flow as follows:

1) Larger friction restricts the original flow for a material with plastic anisotropy. On the \( z \)-axis compression, the ratio of \( \varepsilon_z \) to \( \varepsilon_x \) approached unity when the friction became higher. These friction conditions were judged from the surface view, profile and roughness, and the mean pressure.

2) The diagrams of the ring-compression test were modified with Hill's constants which were determined by the small-cube-compression test under well-lubrication. It is better to use the appropriate diagrams to estimate the friction in ring compression test, for a material with plastic anisotropy.
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