Cyclic Compressive Load Measurement Using Electrodeposited Copper Foil

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Abstract
A fundamental study on a method that uses electrodeposited copper foil to measure cyclic compressive load was carried out in this report. When copper foil is adhered to the side of a cylindrical element inserted in a contact area, grain growth is caused by cyclic compressive stress. A basic equation among grain growth density, compressive stress amplitude and number of cycles is derived in this report. If the increasing rate of grain growth is arranged by compressive strain amplitude, the relationship between them does not depend on the material of the cylinder. If some materials are chosen as the cylindrical element, the grain growth occurred in a wide range of compressive stress amplitudes. This means that a wide range of compressive load can be measured without changing the shape of cylindrical element.

Key words
Stress-Strain Measurement, Fatigue, Contact Problem, Nondestructive Inspection, Copper Electroplating Method

1. Introduction
It is important in design situations to know the magnitude of contact load in machine elements. Especially with repeated contact load, metal fatigue can cause fractures in the machine. Typical load/pressure measurement elements are pressure sensitive film [1] and load cells [2]. Using pressure sensitive film is a simple and easy technique, but cyclic pressure measurement is not generally possible. Using load cells is effective for cyclic load measurement. However, it is not sufficient for elements assembled to narrow space and elements in sealed casing, since an output line to the outside is necessary.

The copper electroplating method is an experimental stress measurement method that uses the grain growth to measure cyclic stress in a local area [3] [4]. Since the grain growth density is controlled by the shearing stress amplitude and the number of cycles, the shearing stress amplitude can be calculated based on the grain growth density after the prescribed number of cycles [5]. The above results have been recognized when the normal stress perpendicular to the surface is zero. However, it has been confirmed that grain growth occurs even when the copper foil is inserted in a contact area that exerts cyclic pressure [6]. In this case, the grain growth density is influenced not only by the pressure amplitude and number of cycles but also by the pressure ratio \( R = \frac{p_{\text{max}}}{p_{\text{min}}} \) [7]. The surface roughness of the foil decreases with increasing \( R \), since an increase in the pressure ratio means an increase in the mean pressure \( p_{\text{m}} \). Therefore, this increases the real contact area of the foil. Since this causes a decrease of the real contact pressure amplitude, the grain growth density is considered to be influenced by the pressure ratio. Therefore, it is necessary to measure the pressure ratio to detect the pressure amplitude.

With these considerations, we examined a new method that can measure the compressive load amplitude even if the pressure ratio is unknown. If the copper foil is adhered to the side of a cylindrical element inserted in the contact area, the grain growth is caused by cyclic compressive stress. Since the copper foil is not subjected to the pressure directly, the grain growth is not expected to be influenced by the pressure ratio. Therefore, it should be possible to apply this method to elements that cannot be measured by load cells, since this new method does not need an output line. Moreover, it can be expected that the grain growth can occurs in a wide range of compressive stress amplitude by changing the cylinder material, since the grain growth is considered to be controlled by strain amplitude. First, the relationship among compressive stress amplitude, number of cycles, and grain growth density was investigated using an aluminum alloy and steel as cylinder materials. The influence of the pressure ratio on the grain growth density was also investigated. Second, a basic equation among grain growth density, compressive stress amplitude and number of cycles was derived based on the experimental results. Finally, the compressive stress range at which the grain growth occurred was estimated in various cylinder materials.

2. Experimental Procedure
2.1 Production of electrodeposited copper foil
A stainless steel plate polished by buffing was electroplated with a copper sulfate solution [3]. Composition of plating solution and plating condition are shown in Table 1. The deposited copper layer was stripped from the stainless steel plate. This deposited layer is called a copper foil. The sheet size of copper foil obtained by this procedure is about 200 mm \( \times \) 100 mm. All subsequent experiments were carried out by cutting this single sheet of copper foil to small pieces. The copper foil was about 20 \( \mu \text{m} \) thick and the grain size was about 1 \( \mu \text{m} \) [4].

2.2 Test specimen and testing machine
Aluminum alloy (A7075) and carbon tool steel (SK-3) were used for a cylindrical element. Table 2 shows the moduli of elasticity of the two materials [8]. Figure 1

Table 1 Composition of plating solution and plating conditions

<table>
<thead>
<tr>
<th>Composition of plating solution and plating conditions</th>
<th>( \text{plating solution} )</th>
<th>( \text{plating condition} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper sulfate 5hydrate ( \text{CuSO}_4 \cdot 5\text{H}_2\text{O} )</td>
<td>( \text{g} )</td>
<td>250</td>
</tr>
<tr>
<td>Sulfuric acid ( \text{H}_2\text{SO}_4 )</td>
<td>( \text{g} )</td>
<td>80</td>
</tr>
<tr>
<td>Distilled water ( \text{H}_2\text{O} )</td>
<td>( \text{g} )</td>
<td>1000</td>
</tr>
<tr>
<td>Current density</td>
<td>( \text{A/m}^2 )</td>
<td>180</td>
</tr>
<tr>
<td>Bath voltage</td>
<td>( \text{V} )</td>
<td>0.8</td>
</tr>
<tr>
<td>Plating time</td>
<td>( \text{min} )</td>
<td>40</td>
</tr>
</tbody>
</table>

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shows the geometry and dimensions of the test cylinder. The top and bottom of the test cylinder were finished by grinding so that each plane would be parallel. A sheet of copper foil 2×4 mm was adhered at two places in the test cylinder. The dimensions of the test cylinder should be considerably smaller than the one shown in Fig. 1, since the grain growth occurs in a microscopic region. However, since manufacturing a small cylinder and bonding the copper foil is technically difficult, a large one was used as a basic experiment.

2.3 Experimental procedure

Figure 2 shows the loading device used for the calibration test. The diameters of the convex parts of the upper and lower blocks were the same size as the test cylinder. Each convex part was also finished by grinding. The loading device material was carbon tool steel (SK-3), and the quenching and the tempering processes were done before the grinding finish. The test cylinder was inserted between convex parts of the upper and lower blocks and the test was carried out under various testing conditions. Adhesive tape was used to fix the test cylinder to the lower block. A sleeve was also used so that the center axis of the upper block would correspond with the center axis of the lower block during testing.

The pulsating compression test was carried out under various combinations of compressive stress amplitude \( p_d \), number of cycles \( N \), and pressure ratio \( R \) by installing the loading device in the closed-loop servo-hydraulic testing machine. Figure 3 shows the nomenclature for the constant amplitude loading pattern. \( R \) is expressed as

\[
R = \frac{p_{\text{min}} - p_d}{p_{\text{max}} - p_d}.
\]

The testing wave form was a sin curve and the frequency was 60 Hz. The copper foil was electrochemically polished and etched after the cyclic test. Images of the grown grains were captured using a personal computer with a digital camera installed on an optical microscope (200x magnification), and image processing software was used to measure the grain growth density \( r^* (=\text{grain growth area} / \text{measurement area}) \). Figure 4 is a microphotograph of some of the grown grains.

3. Results and Discussion

3.1 Influence of pressure ratio on grain growth density

Figure 5 shows the effect of pressure ratio \( R \) on grain growth density \( r^* \) obtained under three experimental conditions. The compressive stress amplitude \( p_d \) and the number of cycles \( N \) were the same under each experimental conditions. The filled-in black symbols represent the results of using an aluminum alloy test
cylinder, and the filled-in white symbols represent the results of using a carbon tool steel test cylinder. Under each experimental conditions, the grain growth density clearly had almost the same values even when the pressure ratios were different. Therefore, we conclude that pressure ratio \( R \) does not affect the grain growth density \( r^* \). In other words, the grain growth density \( r^* \) depends only on the compressive stress amplitude \( p_d \) and the number of cycles \( N \) and is not influenced by the mean stress \( p_m \). Therefore, as we expected, the compressive load can be measured using this new method even when the mean pressure \( p_m \) (or pressure ratio \( R \)) is unknown.

### 3.2 Relationship between grain growth density and number of cycles

The relationship between grain growth density \( r^* \) and number of cycles \( N \) under various compressive stress amplitudes \( p_d \) was investigated under constant pressure ratio \( R \) \((R=0.2)\), since the results given in the previous section showed that the pressure ratio does not affect the grain growth density. Figure 6 shows the results obtained using two kinds of materials as the test cylinder. The solid lines in Fig. 6 express the line approximated by the least squares method and the dashed lines show an experimental formula that will be described later. The grain growth density increased with increased compressive stress amplitude and number of cycles in each test cylinder. In addition, when the material of the test cylinder was different, the compressive stress amplitude where the grain growth occurred was also different. Namely, the compressive stress amplitude at which the grain growth occurred in carbon tool steel was almost twice as large as that in aluminum alloy. The reason for this is considered to be as follows. It has been clarified that the grain growth density is controlled not by the stress amplitude but by the strain amplitude [4]. Since the Young’s modulus of aluminum alloy is smaller than that of carbon tool steel as shown in Table 2, the strain amplitude in aluminum alloy is larger than that in carbon tool steel even if the stress amplitude is the same. Therefore, grain growth occurs on copper foil at smaller compressive stress amplitude in aluminum alloy than in carbon tool steel. This means that the compressive stress range at which the grain growth occurs can be adjusted by changing the test cylinder material.

### 3.3 Deriving the experimental formula

It was cleared that the grain growth density \( r^* \) is only controlled by compressive stress amplitude \( p_d \) and number of cycles \( N \). Therefore, if the relationship among \( r^* \), \( N \) and \( p_d \) is formulated, \( p_d \) can be obtained by measuring \( r^* \) in the prescribed \( N \). From this viewpoint, we derive the experimental formula. The grain growth in copper foil is considered to be a kind of thermal recrystallization [9] which is expressed as the rate process [10]. Namely, this growth is caused by supplying mechanical energy instead of thermal energy. According to the conventional report [5], the square root of increasing rate \( \sqrt{\frac{\partial r^*}{\partial N}} \) is expressed as the rate process. Namely, the square roots of slopes drawn

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By examining the data in Table 2, we can observe that the strain amplitude in aluminum alloy is greater than that in carbon tool steel. This indicates that the grain growth density in aluminum alloy is higher than in carbon tool steel. Therefore, the grain growth density depends not only on the compressive stress amplitude but also on the strain amplitude. This is consistent with the observation that the grain growth density increases with an increase in the number of cycles. The graph in Figure 6 shows the relationship between the grain growth density and the number of cycles for two different materials: aluminum alloy and carbon tool steel. The results indicate that the grain growth density in aluminum alloy is significantly higher than in carbon tool steel, even though the compressive stress amplitude is the same. This suggests that the grain growth density is not solely dependent on the compressive stress amplitude, but also on other factors such as the strain amplitude.
in Fig. 6 by solid lines are expressed by the following equation.

\[
\frac{\partial r^*}{\partial N} = A \exp\left(-\frac{U(\sigma)}{kT}\right),
\]

(2)

where \(A\), \(k\), and \(T\) are the frequency factor, the Boltzmann constant and absolute temperature, respectively. Furthermore, \(U(\sigma)\) is the activation energy which is expressed by the following equation in the case of metal fatigue or creep process [11].

\[
U(\sigma) = U_0 - a_0 \sigma,
\]

(3)

where, \(U_0\) is the activation enthalpy and \(a_0\) is the activation capacity, respectively. Since the grain growth phenomenon is a kind of fatigue in copper, Eq. (3) is applicable here. However, the grain growth is not affected by normal stress \(\sigma\) but shearing stress. Since the stress state of test cylinder is uniaxial compression, the shearing stress is expressed as \(\frac{p_d}{2}\). Therefore, \(\frac{p_d}{2}\) can be applied in Eq. (3) instead of normal stress \(\sigma\). The slopes \(\frac{\partial r^*}{\partial N}\) are expressed as follows by substituting Eq. (3) for eq. (2).

\[
\frac{\partial r^*}{\partial N} = A \exp\left(-\frac{U_0 - a_0 (\frac{p_d}{2})}{kT}\right).
\]

(4)

Since all experiments were carried out at room temperature, \(T\) in the above equation is regarded as a same value. Therefore, relationship between \(\frac{\partial r^*}{\partial N}\) and \(p_d\) is expressed as the following equation.

\[
p_d = \alpha \log\left(\frac{\partial r^*}{\partial N}\right) + \beta,
\]

(5)

where \(\alpha\) and \(\beta\) are constants. Fig. 7 shows the semi-log plot of the square roots of slopes shown in Fig. 6 and compressive stress amplitudes. Since the relationship between both is expressed as the straight line in each material, the values of \(\alpha\) and \(\beta\) are obtained by least square method. Table 3 shows the values of \(\alpha\) and \(\beta\). The following equation is obtained by solving above differential equation about \(r^*\).

\[
r^* = N10^{\frac{2(p_d - \beta)}{\alpha}} + f(p_d),
\]

(6)

where \(f(p_d)\) is the only function of \(p_d\) and corresponds to the intercept obtained by extrapolation of the \(r^*-N\) relationship shown in Fig. 6. Since the grain nucleation process occurs before the grain growth in copper foil, the intercept, whose value depends on compressive stress amplitude, becomes not zero but a negative one. Namely, the function \(f(p_d)\) increases with \(p_d\) and approaches zero. The semi-log plot of absolute value of \(f(p_d)\) and \(p_d\) are shown in Fig. 8. The following expression holds since the relationship between both is linear in each material.

\[
|f(p_d)| = m10^{\gamma p_d},
\]

(7)

where \(m\) and \(n\) are constant and these values are shown in Table 3. Therefore, \(r^*\) can be expressed as the following formula from Eq. (6) and (7).

\[
r^* = N10^{\frac{2(p_d - \beta)}{\alpha}} - m10^{\gamma p_d}.
\]

(8)

The relationship between \(r^*\) and \(N\) can be calculated from Eq. (8) in each \(p_d\). The dashed lines in Fig. 6 express the above calculation results and agree well with the experimental values. Table 4 shows a comparison between setting stress amplitude \(p_d\) and the calculated stress amplitude.

Table 3 Experimental coefficients of \(\alpha, \beta, m, \) and \(n\)

<table>
<thead>
<tr>
<th>Material</th>
<th>(\alpha)</th>
<th>(\beta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A7075</td>
<td>1.70\times10^2</td>
<td>4.75\times10^2</td>
</tr>
<tr>
<td>SK-3</td>
<td>4.37\times10^2</td>
<td>1.17\times10^3</td>
</tr>
</tbody>
</table>

Fig. 8 Relationship between \(|f(p_d)|\) and \(p_d\)
The shearing strain amplitude $\gamma_d$ within which grain growth occurs can be considered to be in the range of $1.2 \times 10^{-3}$ to $2.1 \times 10^{-3}$ as shown in Fig. 9. When various materials with the moduli of elasticity shown in Table 6 are used as the test cylinder, the compressive stress range, at which the grain growth occurs, can be estimated from Eq. (9). These results are summarized in Fig. 10. The compressive stress range of one material overlaps with the materials to its right and left. Moreover, Table 6 shows the proof stress $\sigma_{0.2}$ of the materials. Since the range for each material is much smaller than the proof stress $\sigma_{0.2}$, the possibility of fatigue fractures due to cyclic pressure is also considered to be low. The pressure ratio $R$ doesn’t affect the grain growth density as seen in Fig. 5. Therefore, if the pressure ratio does not become large enough to exceed the material strength (e.g. proof stress), the compressive stress range in Fig. 10 can be applied to an arbitrary pressure ratio. Since the grain growth occurs at the wide range of material strength (e.g. proof stress), the compressive stress range in Fig. 10 can be applied to an arbitrary pressure ratio. Since the grain growth occurs at the wide range of material strength (e.g. proof stress), the compressive stress range in Fig. 10 can be applied to an arbitrary pressure ratio.

### 3.4 Compressive stress range of grain growth

When the material of the test cylinder that the copper foil was adhered to was different, the compressive stress amplitude at which the grain growth occurred was different, as shown in Fig. 6. We concluded that this was because the strain amplitude dominates grain growth. Since the shearing strain is responsible for the grain growth, the results shown in Fig. 7 were rearranged using the shearing strain amplitude $\gamma_d$. The shearing strain amplitude $\gamma_d$ is expressed as the following equation by using Young’s modulus $E$ and Poisson’s ratio $\nu$, since the shearing stress amplitude is equal to $p_d/2$ in the case of uniaxial compression.

$$\gamma_d = \frac{(1+\nu)}{E} p_d .$$  \hspace{1cm} (9)

The shearing strain amplitude $\gamma_d$ is calculated by substituting the values of Table 2 for Eq. (9). Figure 9 shows the results obtained by rearranging the square roots of $\varepsilon_r^*/\varepsilon N$ by $\gamma_d$. From the figure, the difference between aluminum alloy and carbon tool steel shown in Fig. 7 becomes small and the relationship between them can be expressed as a single line. Namely, the solid line in the figure is expressed as

$$\gamma_d = \alpha' \log \left( \frac{\varepsilon_r^*}{\varepsilon N} \right) + \beta' ,$$  \hspace{1cm} (10)

where $\alpha'$ and $\beta'$ are constants with the values shown in Table 5. This suggests that the shearing strain amplitude $\gamma_d$ dominates the grain growth in copper foil.

### Table 4 Comparison between setting stress amplitude $p_d$ and the calculated stress amplitude $p_d^*$

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A7075</td>
<td>1.5</td>
<td>90.2</td>
<td>2.0</td>
<td>203.5</td>
<td>1.8</td>
<td>88.6</td>
</tr>
<tr>
<td>SK-3</td>
<td>2.4</td>
<td>90.0</td>
<td>2.5</td>
<td>201.5</td>
<td>2.5</td>
<td>89.3</td>
</tr>
</tbody>
</table>

$p_d^*$ by substituting the setting number of cycles $N$ and measured grain growth density $r^*$ in Fig. 6 for Eq. (8). The calculated stress amplitude $p_d^*$ agrees well with setting stress amplitude $p_d$. Therefore, it is possible to use experimental Eq. (8) to calculate the compressive stress amplitude. The compressive load can be obtained by multiplying the cross section area of the test cylinder.

### Table 5 Experimental coefficients of $\alpha'$ and $\beta'$

<table>
<thead>
<tr>
<th>$\alpha'$</th>
<th>$\beta'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$4.44 \times 10^{-3}$</td>
<td>$1.05 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

### Table 6 Moduli of elasticity and proof stress in various materials used as the test cylinder

<table>
<thead>
<tr>
<th>Material</th>
<th>$E$ [GPa]</th>
<th>$\nu$</th>
<th>$\sigma_{0.2}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AZ61</td>
<td>40</td>
<td>0.30</td>
<td>250</td>
</tr>
<tr>
<td>A7075</td>
<td>72</td>
<td>0.33</td>
<td>500</td>
</tr>
<tr>
<td>Ti-6Al-4V</td>
<td>106</td>
<td>0.32</td>
<td>950</td>
</tr>
<tr>
<td>Cu-Be</td>
<td>130</td>
<td>0.30</td>
<td>950</td>
</tr>
<tr>
<td>SK-3</td>
<td>206</td>
<td>0.30</td>
<td>-</td>
</tr>
</tbody>
</table>
4. Conclusion
A fundamental study of a method that uses the grain growth in copper foil to measure cyclic compressive load is examined in this report. Namely, the copper foil was not directly inserted in the contact area but adhered to the side of a test cylinder inserted in the contact area in order to reduce the effect of the pressure ratio on grain growth density. Grain growth density was investigated under various combinations of compressive stress amplitude, number of cycles, and pressure ratio. Moreover, the compressive stress range at which the grain growth occurred was estimated in various cylinder materials.

The results obtained are summarized as follows.
(1) Grain growth density $r^*$ depends only on compressive stress amplitude $p_d$ and number of cycles $N$ and is not influenced by pressure ratio $R$.
(2) If the grain growth density $r^*$ is measured for a prescribed number of cycles $N$, the compressive stress amplitude $p_d$ can be determined using experimental formula (8).
(3) If the square root of an increasing rate $\sqrt{r^*/N}$ is arranged by the shearing strain amplitude $\gamma_h$, the relationship between them does not depend on the material of the test cylinder. This suggests that the shearing strain amplitude is the dominant factor in the grain growth in copper foil.
(4) Since the grain growth occurs at the wide range of compressive stress by choosing an appropriate material as the test cylinder, a wide range of compressive load can be measured without changing the shape of cylindrical element.

Nomenclature

- $A$ frequency factor
- $a_0$ activation capacity
- $E$ Young’s modulus
- $k$ Boltzmann constant
- $N$ number of cycles
- $\nu$ Poisson’s ratio
- $p_d$ compressive stress amplitude (pressure amplitude)
- $p_d^*$ calculated compressive stress amplitude
- $p_m$ mean compressive stress (mean pressure)
- $p_{max}$ maximum compressive stress (maximum pressure)
- $p_{min}$ minimum compressive stress (minimum pressure)
- $R$ pressure (stress) ratio
- $r^*$ grain growth density
- $T$ absolute temperature
- $U(\sigma)$ activation energy
- $U_0$ activation enthalpy

References