1. Introduction

The structural health monitoring of bridges and ships that have been in service for a long period is required in order to avoid fracture due to their aging degradation. The estimation of fatigue damage is very important to ensure the reliability of these infrastructures. Although strain gauges and fatigue sensors have been used, a new sensing tool called the “smart stress memory patch”, which consists of a pure Cu with thin thickness and small grain size, has been proposed in our previous studies to estimate fatigue damage such as maximum fatigue stress, number of cycles and stress amplitude for structural health monitoring. In this study, the acoustic emission (AE) activity of pure Cu specimens heat treated under several conditions was investigated because the maximum fatigue stress can be estimated on the basis of the AE onset stress in the Kaiser effect. The obtained AE onset stress was proportional to the yield stress, and the notch sensitivity of the AE onset stress was not observed. The Kaiser effect in Cu specimens with various grain sizes was examined during reloading. The AE onset stress of the Cu specimen with a large grain size during reloading was lower than the previous maximum stress, while the AE onset stress of that with a small grain size was almost equal to the maximum stress in the first loading. The applied maximum stress in fatigue loading was compared with the AE onset stress and the result shows that a suitable stress range for a smart stress memory patch can be obtained using the heat-treated and notch-introduced electrodeposited Cu specimen.

KEY WORDS: acoustic emission; fatigue; structural health monitoring; Kaiser effect; pure Cu.
3 μm has rarely been studied and the factors that depend on the AE onset stress have not been understood. In this study, the AE measurement of pure Cu was conducted to understand the AE behavior of the electrodeposited (ED) Cu with a grain size of a few micrometers. Firstly, factors that affect the AE onset stress were investigated. Furthermore, the Kaiser effect was examined to estimate the applied maximum stress, and lastly, the stress estimated on a basis of AE onset stress was compared with the applied maximum stress in fatigue loading in order to verify the possibility of estimating the maximum fatigue stress using the smart stress memory patch.

2. Experimental Procedure

2.1. Materials

An ED Cu (99.8% purity) of 0.1 mm thickness, which is used for the smart stress memory patch, was prepared, and a rolled Cu (99.96% purity) of 0.2 mm thickness was also prepared for comparison (a rolled Cu of 0.1 mm thickness was also prepared, but it was very difficult to perform AE measurement because it was too soft). The mean grain sizes of these samples were approximately 2 μm for the ED Cu and approximately 30 μm for the rolled Cu. These samples were cut into sections of 40 mm length and 5 mm width. A controlled heat treatment procedure was applied for ED Cu specimens in order to obtain various microstructures. The heat treatment conditions are listed in Table 1. The smoothed and notched specimens were prepared. A single edge notch was introduced into the center of the specimen to investigate the dependence of notch length, and the notch lengths are also shown in Table 1 as normalized notch length $\alpha$ ($\alpha=0$ means smoothed specimen). The notch tip was round-shaped with approximately 150 mm curvature.

2.2. AE Measurement

AE behavior was investigated during tensile loading with a cross-head speed of $1.67 \times 10^{-6}$ m/s. An AE sensor (M304A, Fuji Ceramics Corp.) was attached to the surface of each specimen with glue, and the AE waveform was amplified by the pre-amp (A1002, Fuji Ceramics Corp.) and recorded by continuous wave memory (CWM) system developed by our group. In the AE measurement, the sampling rate was 10 MHz, the total gain was 110 dB, and the high pass filter was 200 kHz. AE measurements were conducted under three conditions. (i) AE measurement for as-received and as-heat treated samples was to investigate the AE behavior and AE onset stress of each sample. (ii) AE measurement in the reloading pattern was to examine the Kaiser effect during reloading. (iii) AE measurement during tensile loading after the fatigue loading pattern was to estimate the maximum fatigue stress from the AE onset stress. In the fatigue loading pattern, the combinations of applied maximum stress and number of cycles were changed as shown in Table 2, because an almost equivalent fatigue damage was applied to the specimens according to the previous study. The fatigue loading was applied under the conditions of a sinusoidal wave with a frequency of 19 Hz and a stress ratio of 0.1. The final state of fatigue loading was return to zero in load. No fatigue crack was introduced under these fatigue conditions because the maximum stress was sufficiently small, so the notch length was unchanged during this fatigue test.

3. Results

3.1. AE Behavior

AE waves of the rolled Cu specimen and as-received ED Cu specimen were measured. The continuous-type AE wave was observed for each specimen unlike in the case of the ultra fine-grained Cu in Ref. 8. The amplitude of the

| Temperature, $T$ / °C | Time, $t$ / min | Grain size, $d$ / μm | Normalized notch length, $\alpha$ |
|-----------------------|----------------|---------------------|-------------------------------|
| as-rec.               | -              | 1-2                 | 0, 0.2, 0.4, 0.5, 0.6, 0.7    |
| 300-10                | 300            | 10                  | 0, 0.2, 0.4                   |
| 300-30                | 300            | 30                  | 2-3                           |
| 300-60                | 300            | 60                  | 4                             |
| 400-30                | 400            | 30                  | 4                             |
| 400-60                | 400            | 60                  | 8                             |
| 450-60                | 450            | 60                  | 15                            |
| 500-45                | 500            | 45                  | 10                            |
| 600-30                | 600            | 30                  | 25                            |

| Maximum stress [MPa] | Cycles      |
|----------------------|------------|
| 30                   | 300,000    |
| 35                   | 100,000    |
| 40                   | 100,000    |
| 45                   | 50,000     |
| 50                   | 50,000     |
AE wave of the ED Cu specimen was lower than that of the rolled Cu specimen. The AE behavior of each sample was evaluated using the root-mean-square (RMS) voltage of the AE wave. The RMS voltage in the rolled Cu specimen changed with simultaneous application of stress because of its high AE activity, while that in the as-received ED Cu specimen started to increase when a certain stress was loaded because of its low AE activity. Thus, it was found that the AE onset stress of the rolled Cu specimen was almost zero, but that of the ED Cu specimen had a value which depends on the heat treatment conditions. These results indicated that the AE onset stress was affected by the AE activity of each Cu specimen.

### 3.2. AE Onset Stress

The dependence of the heat treatment conditions and notch length on the AE onset stress was explored. Figure 1 shows the relationship among stress, strain and RMS voltage of the as-received ED Cu specimen. The AE peak stress, which is the stress when the RMS voltage reaches the peak value, is smaller than the yield stress. In this study, the AE onset stress is determined on the basis of the stress at the cross point of the noise level and the increasing RMS voltage as shown in Fig. 1. The scattering in the relationship between AE onset stress and AE peak stress was investigated using many as-rolled ED Cu specimens, and it was sufficiently small so that two or three specimens were tested under other conditions.

The effect of the AE peak stress on the AE onset stress was examined using the smooth ED Cu specimens with various grain sizes, as shown in Fig. 2. The AE onset stress decreases with the AE peak stress linearly and it is almost zero when the AE peak stress is about 50 MPa. The relationship between the AE peak stress and yield stress is also linear as shown in Fig. 3. These relationships are represented as,

\[\sigma_{AE} = 0.615\sigma_{peak} - 24.7 \quad (1)\]
\[\sigma_Y = 1.2\sigma_{peak} - 4.8 \quad (2)\]
\[\sigma_{AE} = 0.51\sigma_Y - 22.2 \quad (3)\]

where \(\sigma_{AE}\) is the AE onset stress, \(\sigma_{peak}\) is the AE peak stress and \(\sigma_Y\) is the yield stress. Thus, the AE onset stress is proportional to the AE peak stress and yield stress. It was experimentally demonstrated that the AE onset stress can be controlled by adjusting the yield stress.

*Figure 4* shows the effect of the notch length on the AE onset stress using ED Cu specimens with various notch lengths and demonstrates that the AE onset stress decreases as the notch length increases. However, it was considered that this decrease in the AE onset stress is caused by the decrease in the cross-sectional area because the AE onset stress divided by the notch ligament length was almost the same, as shown in *Fig. 5*, and it was concluded that the notch sensitivity cannot be observed. It was also demonstrated that the controlled range of the AE onset stress becomes wider depending on the notch length.

### 3.3. Kaiser Effect

The Kaiser effect in rolled and ED Cu specimens with 0.5 normalized notch length heat treated at 400°C for
30 min was examined during the reloading test. Figure 6 shows the result for the rolled Cu specimen; the AE onset stress during the reloading was smaller than the applied maximum stress at the first loading. This result demonstrated that the Kaiser effect in the rolled Cu specimen cannot be realized. On the other hand, the AE onset stress of the heat treated ED Cu specimen during the reloading is almost equal to the applied maximum stress, and the Kaiser effect can be verified, as shown in Fig. 7.

3.4. Estimation of Maximum Fatigue Stress

The fatigue loading was conducted on the ED Cu specimens (400°C, 30 min, $\alpha=0.4$ and 0.5) and then these AE behaviors were measured to estimate the applied maximum stress during the fatigue loading. Figure 8 shows the AE behavior of the ED Cu specimen (400°C, 30 min, $\alpha=0.4$) which had been applied the fatigue loading at maximum stress of 30 MPa and 300,000 cycles. This result demonstrates that the applied maximum stress can be estimated on the basis of the AE onset stress. The relationship between the applied maximum stress and AE onset stress is plotted in Fig. 9. In the case of the specimen with 0.5 normalized notch length, the maximum stresses of 45 and 50 MPa cannot be estimated. On the other hand, the applied maximum stress between 30 and 50 MPa can be estimated using the ED Cu specimen with 0.4 normalized notch length.

4. Discussion

4.1. AE Onset Stress

The AE activity during tensile loading increases as the yield stress decreases. It is considered that this tendency is related to the mobility of the dislocation. It is well known that the yield stress depends on grain size and dislocation density. The movement of the dislocation is prevented by the grain boundary. The mean free path of dislocation in the pure metal corresponding to the slip length depends on the grain size. According to Baram and Rosen,6,7) the AE activity increases with grain size for grain sizes below 70 µm. Consequently, the AE activity increases with grain size in the grain size range used in this study.

The effect of white noise, which is background noise during AE measurement, is also taken into account to consider the AE onset stress of the ED Cu specimen because the white noise in the AE measurement is an inevitable

Fig. 5. Notch sensitivity of ED Cu specimen.

Fig. 6. AE behavior of rolled Cu specimen during reloading (400°C, 30 min, $\alpha=0.5$).

Fig. 7. AE behavior of ED Cu specimen during reloading (400°C, 30 min, $\alpha=0.5$).

Fig. 8. AE behavior of ED Cu specimen (400°C, 30 min, $\alpha=0.4$) after fatigue loading with $\sigma_{\text{max}}=30$ MPa and 300,000 cycles.

Fig. 9. Relationship between AE onset stress and applied maximum stress of ED Cu specimen after fatigue loading.
problem. If the AE activity per unit time is very large, the white noise can be ignored. However, it is not negligible in this study because the AE signal at the early stage is smaller than the white noise. Consequently, the RMS voltage of the specimen, in which the AE peak stress is lower than 50 MPa, increases with the loading, while the AE onset stress has a certain value in the case of the specimen with a high AE peak stress because the AE signal is very small.

4.2. Kaiser Effect

No Kaiser effect could be observed in the case of the rolled Cu specimen. A similar report was also described in the review by Skal’skyi et al. The reason why no Kaiser effect in the rolled Cu specimen was observed is considered as follows. In Fig. 6, the RMS voltage increases slightly at 24 s during unloading. This phenomenon is well known as the unload emission due to the AE signals of the Bauschinger effect. According to this study, it was demonstrated that the acoustic emission during unloading is due to the Bauschinger effect and materials that show unload emission do not show a Kaiser effect. On the other hand, the Kaiser effect in the ED Cu specimen (heat treated at 400°C for 30 min, α=0.5) can be observed. The influence of the Bauschinger effect is negligible because the signal-to-noise ratio is small compared with that of the rolled Cu specimen.

4.3. Estimation of Maximum Stress

In the case of the specimen with 0.5 normalized notch length, the maximum stresses of 45 and 50 MPa cannot be estimated. This is because the yield stress of this specimen is small and the Kaiser effect cannot be observed as well as in the case of the rolled Cu specimen. On the other hand, the applied maximum stresses of 45 and 50 MPa can be estimated using the ED Cu specimen with 0.4 normalized notch length. This result demonstrates that the higher maximum stress cannot be estimated using the specimen with lower yield stress. Therefore, it is found that the ED Cu specimen with 0.4 normalized notch length is appropriate as the sensor that can be used to estimate the maximum stress between 30 and 50 MPa.

5. Conclusions

The AE behavior of the pure Cu specimen with thin thickness and small size was investigated for a smart stress memory patch. The conclusions are as follows.

1) The AE behavior of the ED Cu specimen with a grain size of a few micrometers was investigated, and its AE waveform, as well as the typical waveform of fcc metals, is of the continuous type. The AE onset stress was evaluated using the RMS voltage of the AE wave, and it was found that the AE onset stress of the rolled Cu specimen is almost zero but that of the ED Cu specimen has a value.

2) The effect of the microstructure and geometry of the specimen on the AE onset stress was evaluated using the specimens with various grain sizes and notch lengths. It was found that the AE onset stress can be controlled by adjusting the yield stress and notch length. In the case of low yield stress (about 50 MPa), the AE onset stress is close to zero.

3) Although no Kaiser effect can be observed in the case of the rolled Cu specimen, it can be confirmed in the cases of the ED Cu specimens and the previous maximum stress can be estimated during reloading.

4) In the case of estimation of the maximum fatigue stress between 30 and 50 MPa, the ED Cu specimen with 0.4 normalized notch length, heat treated at 400°C for 30 min, can be appropriate as the sensor.

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REFERENCES

1) S. Nambu and M. Enoki: Mater. Trans., 48 (2007), 1244.
2) S. Nambu and M. Enoki: ISIJ Int., 47 (2007), 1687.
3) H. Hatano, H. Tanaka, R. Horiuchi and N. Niwa: J. Jpn. Inst. Met., 39 (1975), 675.
4) H. C. Kim and T. Kishi: Phys. Stat. Sol. a, 55 (1979), 189.
5) R. C. Bill, J. R. Frederick and D. K. Felbeck: J. Mater. Sci., 14 (1979), 25.
6) J. Baram and M. Rosen: Mater. Sci. Eng., 45 (1980), 255.
7) J. Baram and M. Rosen: Mater. Sci. Eng., 47 (1981), 243.
8) A. Vinogradov: Scr. Mater., 39 (1998), 797.
9) A. Vinogradov, V. Patlan, S. Hashimoto and K. Kitagawa: Philos. Mag. A, 82 (2002), 317.
10) K. Ito and M. Enoki: Mater. Trans., 48 (2007), 1221.
11) V. R. Skal’s’kyi, O. E. Andreikiv and O. M. Serhienko: Mater. Sci., 39 (2003), 86.
12) J. R. Frederick and D. K. Felbeck: ASTM STP, 505 (1971), 129.