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GENERATED DURING PLASTIC DEFORMATION OF COPPER

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EFFECT OF GRAIN SIZE ON THE ACOUSTIC EMISSION
GENERATED DURING PLASTIC DEFORMATION OF COPPER

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SUMMARY

Acoustic signals emitted from plastically deformed copper specimens were analyzed with respect to the grain size and strain rate employing a kinematic model. The data are interpreted in terms of an acoustic emission parameter related to the behavior of copper while undergoing plastic deformation.

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1. INTRODUCTION

In a recent paper [1], the acoustic emission generated from polycrystalline Al-1100 samples during plastic deformation, was analyzed with respect to the strain rate and grain size. A kinematic model was proposed to account for the observed behavior. An experimental acoustic emission parameter, equivalent to the average energy of the acoustic events, has been shown to relate satisfactorily with the calculated energy of moving dislocations during the deformation process.

In the present paper, acoustic emission data obtained during plastic deformation of polycrystalline copper with different grain sizes, are reported. The data are interpreted in terms of the acoustic emission parameter [1].

2. EXPERIMENTAL

Polycrystalline, commercial grade Cu of 99.99 percent purity was used to machine flat tensile specimens 50 mm long, 12.5 mm wide and 2 mm thick at the gauge section. A variety of grain sizes, in the range between 40 and 130 μ m was obtained by a controlled recrystallization procedure, Table 1. The samples were water cooled after the heat treatment. The grain size was determined employing the standard ASTM technique. Typical grain sizes are shown in Fig. 1. Chemical cleaning of the specimens was performed prior to the tensile testing in order to remove superficial oxide films.

Plastic deformation was carried out on an INSTRON tensile testing machine, at constant crosshead velocities, up to stresses equivalent

to 90 percent of the ultimate tensile strength. Strain was determined by a 25 percent gauge elongation extensometer, and simultaneously chart-recorded with the applied stress. The constant strain rate was $1.6 \times 10^{-3} \text{ s}^{-1}$ for all samples. The acoustic emission data-acquisition system was described in [1].

3. RESULTS

The dependence of the acoustic emission parameters on grain size is shown in Table 2. The numerical results are presented as averages. Figure 2 shows a typical behavior of tensile load, cumulative counts and count rate vs. strain. Figure 3 exhibits the acoustic count rate behavior with variation of the grain size. The dependence of other acoustic emission variables: cumulative counts, cumulative events, count rate maxima and average counts per event, on grain size is shown in Fig. 4.

The cumulative number of counts passes through a maximum value for the $70\mu\text{m}$ grain size, and so does the cumulative number of acoustic events and the maximum average count rate. The behavior of Cu is similar to that reported for Al-1100 [1] with the exception of two points: the maximum values for Al were attained at a lower average grain size ($55\mu\text{m}$), and the acoustic activity of Cu is higher by a factor of 20 than the activity in Al, when comparing tensile tests at the same strain rates and grain sizes.

The $\Sigma C / \Sigma E$ parameter, which is a measure of the energy of the acoustic event [2], shows an entirely different behavior for Cu (Fig. 4) than for Al. The parameter passes through a minimum value

for the intermediate grain sizes (60–90 μm) instead through a maximum, as was observed for Al [1]. The acoustic count rate dependence upon grain size, as shown in Fig. 3, exhibits the following behavior: the maximum count rate is attained at the yield point only for the samples with an intermediate grain size, showing significant acoustic activity in the plastic deformation range. The 130 μm grain size specimens do not emit any acoustic signals during yielding, but only at plastic strains of 3 percent and higher. Acoustic emission at similar plastic strains was also detected in the Al samples of a 120 μm grain size [1]. No emission was detected in Al samples of smaller grain size. In contrast, all Cu specimens exhibit acoustic activity in the range of the plastic deformation.

The metallographic structures of the stressed samples were examined in order to reveal possible structural changes as a result of the deformation process. Figure 5 shows the morphology for the 40, 70 and 130 μm samples. Slip planes are apparent in all samples. In the specimens with the initial grain size of 130 μm formation of macroscopic subgrains by mechanical twinning was observed. Transmission electron microscopy performed on thin foils taken from a 70 μm grain size specimen, and from a 130 μm specimen, shows the formation of dislocation subcells (Fig. 6a) and the dislocation structure in the twinned region (Fig. 6b). The yield stresses observed for the different grain sizes are not in agreement with the Hall–Petch relationship.

4. DISCUSSION

The dependence of the acoustic emission on the grain size appears to be different for Cu than for Al [1]. The stacking fault energies for these metals are quite different, 238 erg/cm² for Al and 50 erg/cm² for Cu [3]. Stacking fault energy is the dominant factor in controlling the cross slip of dislocations. It was assumed [4] that cross slip is responsible for the generation of acoustic emission. This assumption should lead to a higher acoustic activity in Al than in Cu. But this is in contradiction with the present experimental data showing that for Cu specimens of 70 μ m grain size, strained at a rate of $1.6 \times 10^{-3} \text{ s}^{-1}$, the acoustic activity was found to be 20 times as much as that for Al [1].

The effect of grain size of Cu can be treated within the framework of the kinematic model presented in [1]. The 60, 70 and 90 μ m grain size specimens were heat treated at 540, 600 and 760°C, respectively, where recrystallization and grain growth occurred. Annealing twins were induced during the recrystallization of the deformed matrix [5]. The mean free path for mobile dislocations is reduced, and their density is increased. The energy associated with accelerating and decelerating dislocations in these structures is also reduced, thereby reducing the acoustic emission parameter C/E which is equivalent to the average energy per acoustic event [1]. These specimens exhibited an acoustic emission activity far beyond the yield point (Fig. 3). Late emissions are apparently due to formation of mechanical twins. The twinning stress is known to be dependent on

grain size [6], decreasing with increasing grain size. Consequently, specimens with a grain size of $130\mu\text{m}$, heat treated at 880°C and that have a high probability for mechanically induced twins during the deformation experiments, did not reveal any acoustic activity at the yield point, but only after some extent of plastic deformation. It can, therefore, be concluded that in this case the acoustic activity is due to the formation of mechanical twins.

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Table 1. Heat Treatments and Average Grain Sizes

Average Grain Size [μm]	Recrystallization Temperature [$^{\circ}\text{C}$]	Soaking Time [min]
40	180	30
60	540	40
70	600	35
90	760	30
130	880	30

Table 2. Numerical Results for Cu 99.99 percent

Average Grain Size [μm]	Strain Rate [S^{-1}]	Cumulative Events ΣE	Cumulative Counts ΣC	Average Counts per Event $\Sigma C/\Sigma E$	Average Count Rate Maximum $\bar{C}$ [min^{-1}]
40	1.6×10^{-3}	5	57	1.1	40
60	1.6×10^{-3}	540	850	1.6	300
70	1.6×10^{-3}	800	1350	1.6	430
90	1.6×10^{-3}	330	480	1.4	150
130	1.6×10^{-3}	14	70	5.0	35

CAPTIONS TO FIGURES

Figure 1. Grain sizes of 99.99 percent Cu. Magnification X80.

a) 70 μm , b) 130 μm .

Figure 2. Strain dependence on load, number of counts and count rate of 99.99 percent Cu. A.E. gain 92 dB, strain rate $1.6 \times 10^{-3} \text{ s}^{-1}$.

Figure 3. The grain size dependence of the count rate in 99.99 percent Cu. A.E. gain 92 dB, strain rate $1.6 \times 10^{-3} \text{ s}^{-1}$.

Figure 4. The dependence of the acoustic emission variables upon grain size in 99.99 percent Cu. A. E. gain 92 dB, strain rate $1.6 \times 10^{-3} \text{ s}^{-1}$.

Figure 5. Microstructures of stressed specimens of 99.99 percent Cu. Magnification x 700. a) 40 μm ; b,c) 70 μm ; d,e) 130 μm .

Figure 6. Transmission electron micrographs of 99.99 percent Cu specimens. a) 70 μm grain size, magnification 40000; b) 130 μm grain size, magnification 47000.

Fig. 1a

XBB 805-5568

Fig. 1b

XBB 805-5569

Fig. 2

XBL 805-9546

XBL 805-9547

Fig. 3

XBL 805-9548

Fig. 4

Fig. 5a

XBB 805-5566

Fig. 5b

XBB 805-5567

XBB 805-5565

XBB 805-5564 Fig. 5e

XBB 805-5563 Fig. 5d

Fig. 5c

Fig. 6a

XBB 805-5561

Fig. 6b

XBB 805-5562

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