

## Acoustic Emission Behavior of Martensitic Transformation in Early Stage during Deformation of Cu-Al-Ni Shape Memory Alloy Single Crystals

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### ABSTRACT

Cu-Al-Ni shape memory alloy exhibits a super-elasticity that shows perfect recovery of plastic deformation. The super-elasticity used in this study results from a perfect reversible martensitic transformation. AE behavior during the stress-induced martensitic transformation has been investigated using two types of specimens of Cu-Al-Ni shape memory alloy single crystal, each of which have different stress concentration factors. The rise time of each martensitic transformation in the early stage during tensile deformation was evaluated using a wavelet transformation analysis instead of the slope method of whole waveform in the frequency domain. It was made clear that the shorter rise time was included fairly in the early stage and associated with the nucleation of the martensite regardless of the specimen shape.

### INTRODUCTION

Martensitic transformation is known as a transient shear process in materials. The kinetic property of the transformation must give important information to make clear the nature of the transformation [1]. In general, the martensitic transformation proceeds both by nucleation and growth of martensite plate [2]. The kinetics of the martensitic transformation phenomenon has been measured using transient electrical resistance change in Fe-Ni alloy [3], magnetic permeability change in Fe-Ni alloy [4] and AE method in austenitic stainless steel [5,6]. These results have two shortcomings to explain the kinetic behavior of individual martensite plates. One is that those included the constraints due to grain boundaries because materials used were polycrystalline. Another is that those could not be distinguished between nucleation and growth of martensite plates because of difficulty of in-situ measurement.

In this paper, the kinetic properties of the stress-induced martensitic transformation in two types of specimens of Cu-Al-Ni shape memory alloy single crystal were investigated using AE waveform generated in the early stage during tensile deformation. The AE waveform analysis where the rise time of each martensitic transformation can be obtained due to slope method in the frequency domain has been already conducted in the previous papers [7, 8]. However, the rise time was modified due to a wavelet transformation in the finite specimens because the analysis can be used only in infinite elastic mediums. The martensitic transformation used in this study is the  $\beta_1$  (DO<sub>3</sub> structure)  $\rightleftharpoons$   $\beta_1'$  (18R structure) transformation which can be observed by an optical microscope during tensile deformation at room temperature. Therefore, the kinetics of martensite plates such as nucleation and growth was examined in detail.

### EXPERIMENTAL PROCEDURES

Material used was a Cu-14.1mass%Al-4.1mass%Ni alloy for stress-induced martensitic transformation. It was melted in argon in a high frequency induction furnace and cast into a plate-shaped copper mold. After that it was put into a graphite mold. A specified single crystal of the Cu-Al-Ni alloy was grown due to a seed crystal using Bridgman method at a speed of 32 mm/h. They were solution-treated at 1273K for 1 hr. and then quenched into water at room temperature in order to keep the  $\beta_1$  matrix phase ( $M_s = 250K$ ,  $A_f = 280K$ ). Two kinds of specimens which consist of smooth (specimen No.1, gage size: 12mmx4mmx1.8 mm) and two-side right-angle notched (specimen No.2) specimens to make clear the effect of

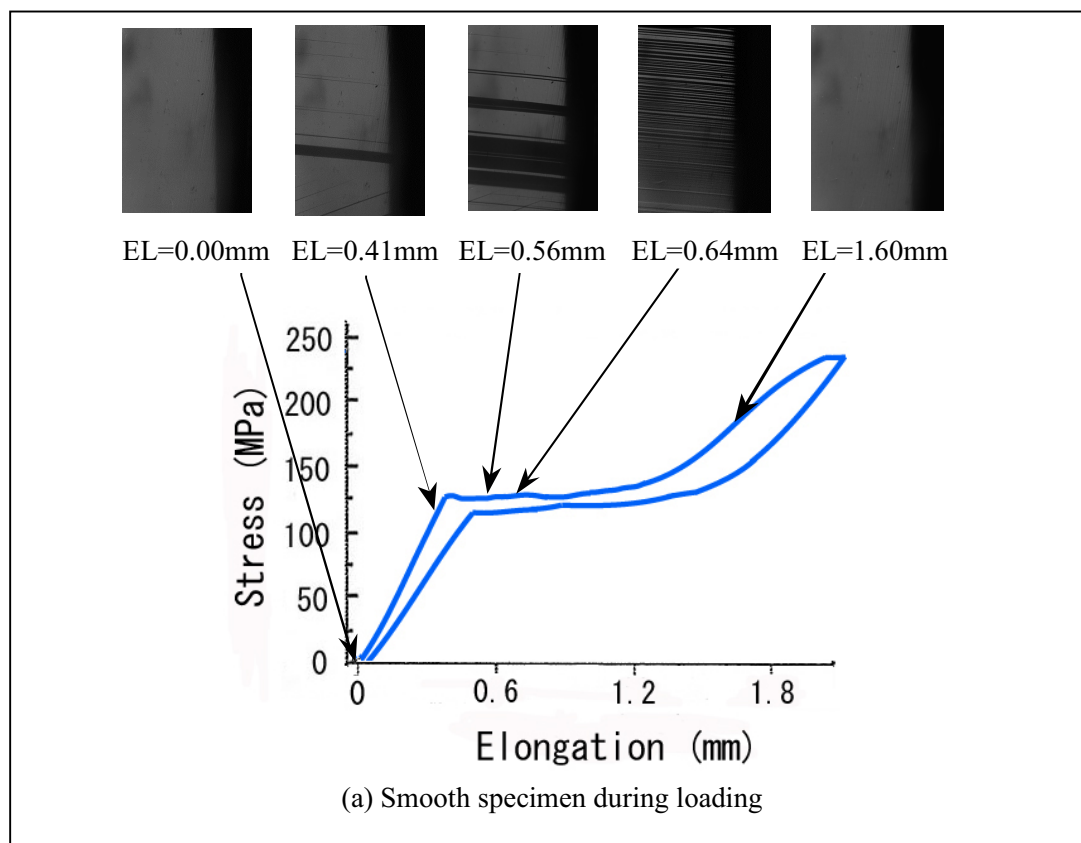
stress concentration on martensitic transformation dynamics were formed with an electron discharge machine, polished mechanically and then electro-polished in a solution of phosphoric acid supersaturated with chromium trioxide. These stress concentration factors in these specimens were 1.01 and 2.65, respectively. The orientation of the single crystal specimen was determined by the back-reflection Laue method. The specimen had (001)[100] in the surface orientation and the tensile direction, respectively. Tensile test was carried out with an Instron-type testing machine at a strain rate of  $5.6 \times 10^{-5} \text{ s}^{-1}$ . Surface appearance during tensile test was observed and photographed microscopically by an optical microscope.

AE measurements were performed using 2-channel AE monitoring system (PAC: MISTRAS-2001). The acoustic signals were detected by two AE transducers (M5W) with wide frequency band that were directly attached on the chucking part of specimen through a rapid binding agent. The distance between two transducers was 20mm. Detected acoustic emission signals were amplified by a constant gain of 60dB through a band-pass filter of 0.1 to 1.2 MHz. AE parameters measured consisted of the AE events, the peak amplitude and the waveforms. Threshold level was 50dB which corresponded to  $316 \mu\text{V}$  at the preamplifier input voltage.

## RESULTS AND DISCUSSION

### (1) Stress-elongation curves and surface appearances during loading and unloading in each specimen

Relations between load-elongation curves, in the smooth and notched specimens during loading are shown in Fig. 1 including typical surface appearances under the stress condition indicated by arrow. All the specimens exhibited super-elasticity and perfectly recovered the matrix phase due to unloading because of the lower  $A_f$  point of the material. The nucleation in both specimens was recognized to start in the elastic region or in the early stage of the tensile deformation.



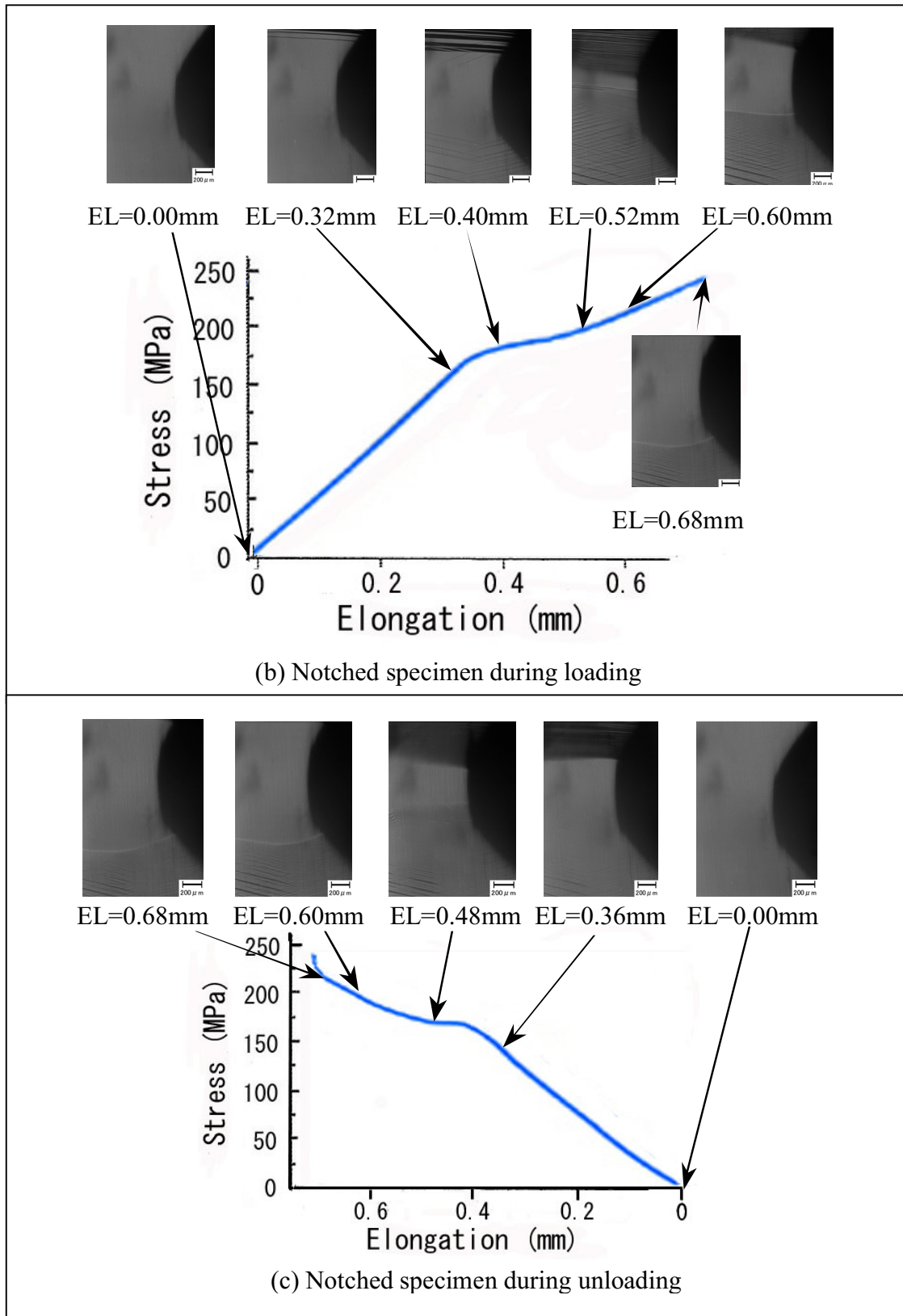


Fig. 1 Relations between load-elongation curves during loading and unloading including each surface appearance under the stress condition indicated by arrow. (a) smooth specimen during loading, (b) notched specimen during loading and (c) during unloading

## (2) AE activity under the different stress conditions

The AE activities were explained in detail in the previous paper [9]. Less number of AE events in the smooth specimen were detected than those in the notched specimen, but higher amplitude in the smooth specimen. It means that the AE activity is related to nucleation and growth of large and not many martensite plates in the smooth specimen and to only nucleation of small and many martensite plates in the notched specimen according to these surface appearances in Fig.1. If the given plastic strain is almost only performed due to the martensitic transformation, it is considered that an amount of transformation is proportional to the given plastic strain energy. So effect of specimen volume on AE activity has been examined with all the specimens given the same plastic strain energy per unit volume and an amount of transformation changed by the specimen volume. Total AE event counts tend to decrease with an increase of the specimen volume. There is no specimen volume effect. Therefore, AE activity does not seem to depend on all the martensitic transformation of material but strongly on the kinetic behavior of the transformation. Especially the tendency becomes stronger under the reverse transformation. It is indicated that it is possible to treat the nucleation and growth of transformation by AE method.

AE behavior in the smooth specimen was different from that in the notched specimen in the early stage of the transformation as mentioned above. In the case of the smooth specimen, martensite plates nucleated at first, extended to single direction, grew to length and width directions and passed through thickness direction during yielding. AE, which occurs sporadically during nucleation in the early stage of the transformation, had small amplitude, but changed medium or high amplitude with growing to length and width directions and higher with generating passed-through martensite plates. In the case of the notched specimen, a lot of small amplitude AEs were detected when a lot of small-sized martensite plates nucleated near the notched roots to two or three directions. There was only small number of medium and high amplitude AEs because a lot of martensite plates nucleated near the notched roots did not grow to width direction because of stress concentration. Many higher amplitude AEs occurred with growing to length and thickness directions.

## (3) Rise time at the source of the martensitic transformation

The rise time at the source of the martensitic transformation has been already analyzed using AE waveform generated in the infinite elastic medium by T. Takashima et al. [7]. The rise time  $\Delta t$  is given by the following equation,

$$m = \partial \log |V(2\pi f)| / \partial \log (2\pi f) = (2\pi f)^2 \Delta t^2 / 8 \quad (1)$$

where  $m$  is the linear slope at the central frequency  $f$  of AE waveform in the frequency domain and  $V(2\pi f)$  is the frequency spectrum of AE waveform. In the case of the finite specimens, the equation (1) is invalid because detected AE waveforms always included various kinds of wave modes that depend on the reflection of waves due to interfaces and surfaces. Therefore, we tried to apply the wavelet transformation (AGU-Vallen wavelet) to decide the first arrival waveform and to modify the rise time in the equation (1). A typical example of the wavelet-transformed detected waveform and  $m$ -value estimation were shown in Fig. 2. The frequency spectrum of the first arrival waveform at 20  $\mu\text{s}$  from the starting point was used to evaluate the  $m$ -value in equation (1). The central frequency was 600 kHz. The rise time obtained was 0.604  $\mu\text{s}$ .

The rise time distributions obtained during loading and unloading in both specimens were shown in Fig. 3. The waveform analysis was performed in the early stage during tensile deformation where the maximum elongation was 0.4 mm. The rise time distribution during loading became broader than that during unloading regardless of the specimen shape. Especially no AE waveform taking the rise time of less than 0.5  $\mu\text{s}$  existed during unloading. The shorter rise time is considered to be associated with the nucleation of the martensite plates, so the same number of waveforms with the rise time of less than 0.5  $\mu\text{s}$  were included during loading in both specimens in spite of the different morphology under the different stress conditions. If the nucleation rate is assumed to be 1000 m/s [8], the initial scale of martensite plate during loading is probable to be fairly several hundreds micrometers. On

the other hand, there was the asymmetry of AE event counts detected between loading and unloading, that is to say, AE event counts during unloading enhanced those during loading as shown in Fig. 3. It is considered that the reverse transformation is easy to nucleate or operate for the strain energy stored during loading. If the nucleation is important to explain the asymmetry, the behavior during unloading may be different from that during loading because the rise time distribution during unloading was at higher level than that during loading. Though it is not clear, AE research from now may play an important role.

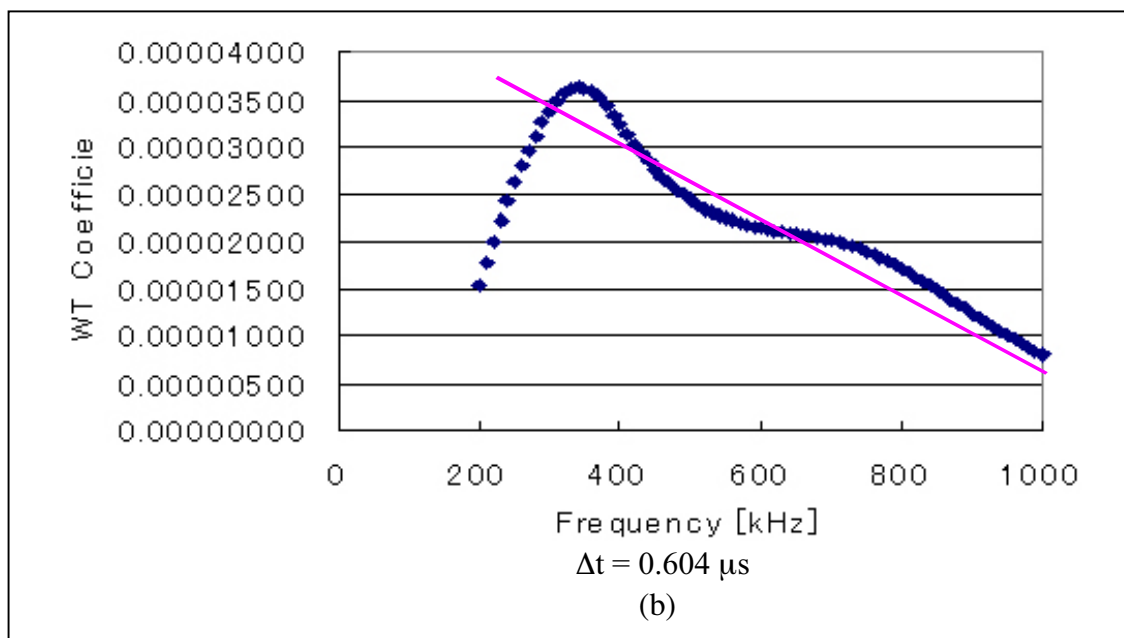
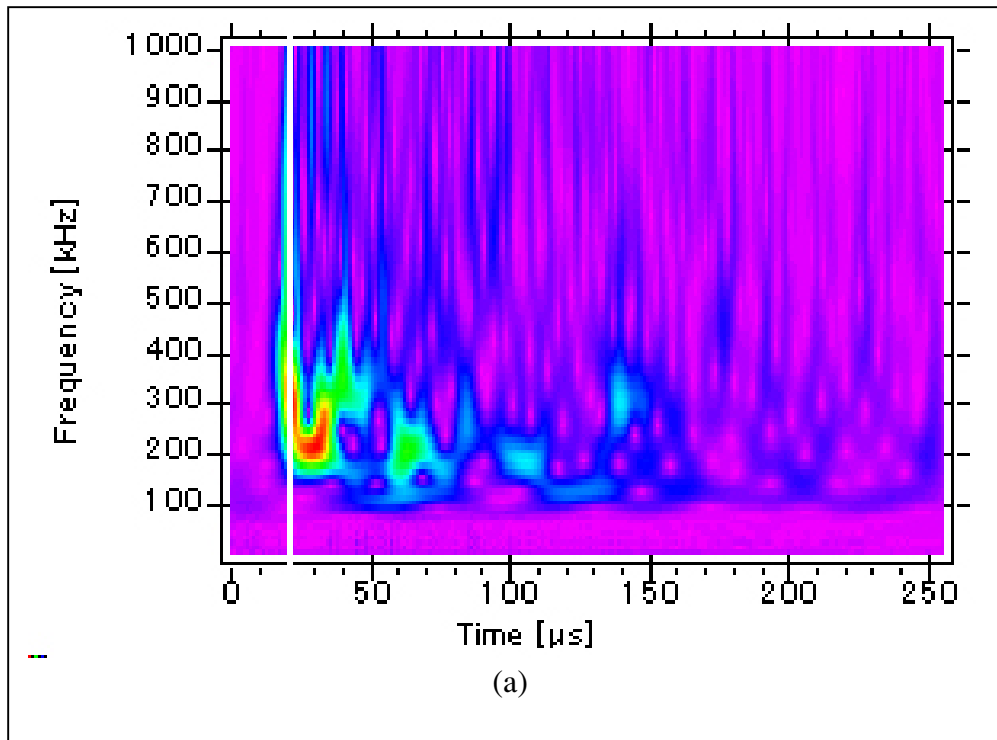
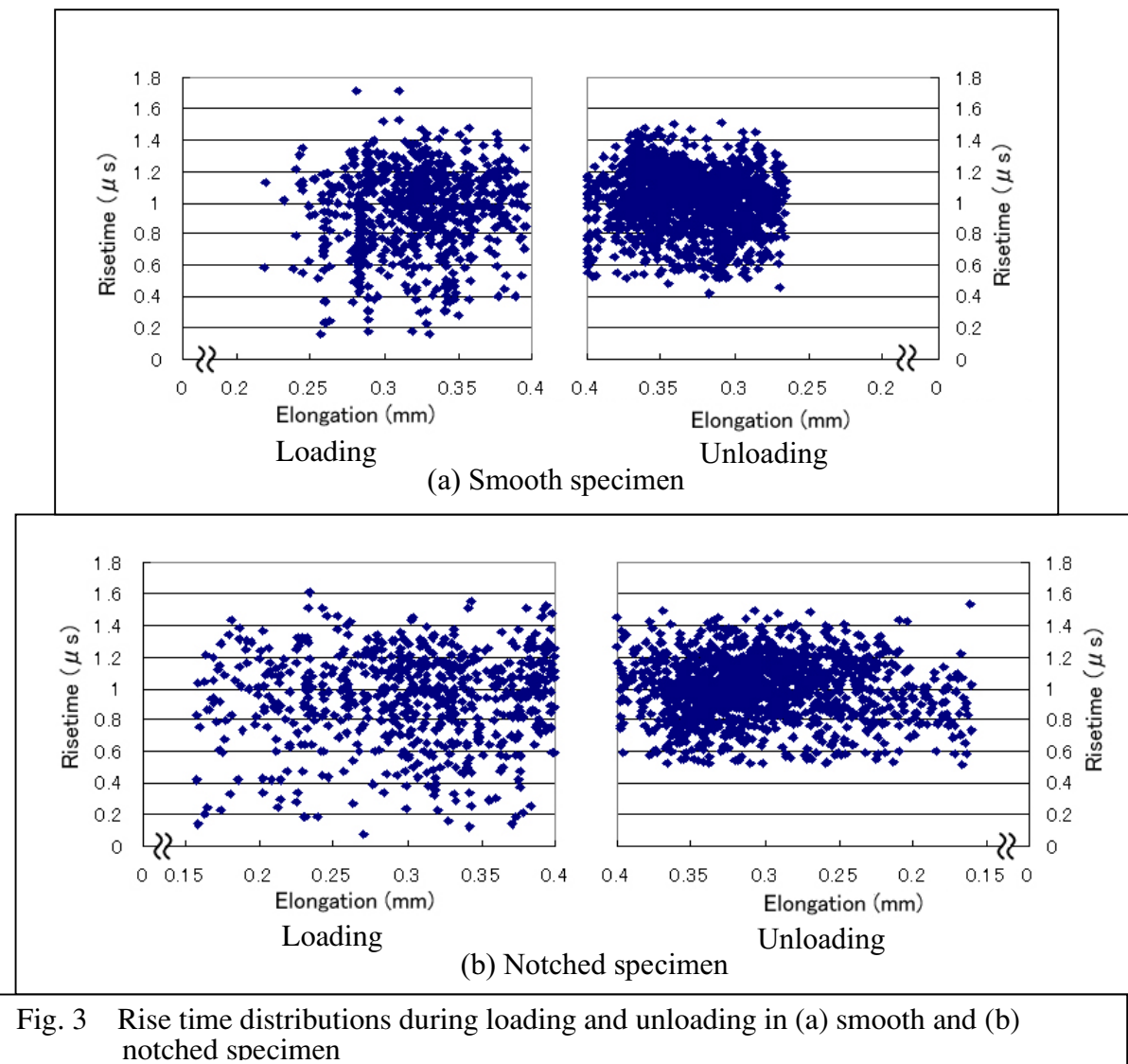


Fig. 2 A typical example of (a) wavelet transformation of a detected waveform and (b) the frequency spectrum of the first arrival waveform at 20  $\mu\text{s}$  from the starting point. The estimated rise time was 0.604  $\mu\text{s}$ .



## CONCLUSIONS

AE behavior during stress-induced martensitic transformation of Cu-Al-Ni shape memory alloy single crystal that exhibits superelasticity has been investigated using the smooth and notched specimens. Results obtained are as follows:

- (1) There was no effect of specimen volume on acoustic emission activity.
- (2) Sequential AE activities that consisted of the acoustic emission event counts, the amplitude and the waveforms in the smooth specimen were different from that in the notched specimen because of different stress concentration.
- (3) AE method is effective to evaluate such kinetic processes such as nucleation and growth of martensitic transformation.

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