Effect of ultrasonic vibration on stress relaxation in micro-compression test with step motion

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Abstract
In this study, to promote stress relaxation effect by the servo actuated step motion that stops the die motion at regular interval, a novel microforming process with combining ultrasonic vibration and the step motion was proposed. To investigate the effect of ultrasonic vibration on stress relaxation by step motion, a micro-compression test was carried out in different scale dimension with the specimen size of 0.5, 1.0 and 2.0mm in diameter and height. Stress relaxation by step motion was repeated for 6 times at constant strain interval. Ultrasonic vibration with amplitude of 1.2 and 2.4 μm was applied on the axial direction during the stress relaxation by step motion. As results, in the all process conditions, the stress drop increased with decreasing the specimen size. To investigate the size dependency of the effect of ultrasonic vibration on stress relaxation, the stress drop in the surface and inner grains was calculated based on the surface grain theory. The result showed that the stress drop in the surface grains was larger than that in the inner grains in similar scale dimension. Additionally, the stress drop in the surface grains increased with decreasing the specimen size. The possibility of improving the material formability by this process was experimentally demonstrated.

Key words: Micro compression test, Ultrasonic vibration, Step motion, Stress relaxation, Size effect

1. Introduction

Microfabrication technology has been receiving much attention with the growing demands for microparts in automobile, biomedical and electronic components. Microforming process is well known as the miniaturization of conventional metal forming processes and one of the promising technologies to fabricate submillimeter scale parts or components (Geiger, et al., 2001). This microforming process has great advantages such as high production rate, less waste, and near-net-shape characteristics.

However, when the specimen size is scaling down from macro to micro scale while the shape and the grain size are kept constant, so-called size effects occur. The material behavior in microforming is mainly influenced by two size effects. One is caused by the specimen size and the other is caused by grain size of the specimen. With decreasing the specimen size, which means the surface grains to volume increases, the flow stress decreases. This is because dislocations in the surface grains are less restricted than that in the inner grains. With increasing the grain size, which means the number of grains in the material increases, inhomogeneous material flow occurs. The reason for this effect is due to the random orientation and size of each single grain. As results, size effects cause some issues such as low formability and forming accuracy (Vollertsen, et al., 2009). Therefore, the enhancement of the material flow during the process is required. As an approach to enhance the material deformation, ultrasonic vibration has been applied to the microforming processes such as micro-extrusion (Bunget and Ngaile, 2011), micro-upsetting (Hung and Tsai, 2013 and Yao, et al., 2012), micro-forging (Kosuge and Yang, 2012), micro-deep drawing (Huang, et al., 2014). In particular, Hung et al. (2013) demonstrated that the reduction of flow stress by ultrasonic vibration becomes more significant with decreasing the process dimensions.

On the other hands, in macro metal forming, the servo actuated step motion that stops the die motion at regular interval was devised and succeeded in improving the forming limit of deep drawing process by stress relaxation
phenomenon (Yamashita, et al., 2012). According to Hariharan et al. (2013), this phenomenon is attributed to the redistribution of dislocations during stress relaxation. Ultrasonic vibration also causes reduction of flow stress by promoting the diffusion of dislocations (Hung and Tsai, 2013). Thus, combining with ultrasonic vibration, the stress relaxation by step motion would be enhanced to improve the formability. Furthermore, the effect of the grain structure on the stress relaxation, which seems to become more dominant in microforming, has not been well discussed. Since the stress reduction by ultrasonic vibration is larger for the smaller specimen, the ultrasonic vibration would be effective in the stress relaxation in microforming. Within these backgrounds, the effect of ultrasonic vibration on stress relaxation by the servo actuated step motion was investigated in the present study. To clarify the size dependency of stress relaxation by ultrasonic vibration, a micro-compression test was performed.

2. Experimental equipments and conditions

The material used is brass (JIS: C3604) with different size of 0.5, 1.0 and 2.0mm in diameter and height. To compare the material behavior between the different scale dimensions, these samples are machined from the same material, which has the average grain size of 12 μm. A scale factor $\lambda$ was used to represent the geometric similarity of the specimen size. In the present study, the scale factor of the specimen with the size of $\phi 0.5 \times 0.5$mm is defined as $\lambda =1$. The scale factor for the specimens with the size of $\phi 1.0 \times 1.0$mm and $\phi 2.0 \times 2.0$mm are $\lambda =2$ and 4, respectively.

As shown in Fig.1, a novel microforming process combining ultrasonic vibration and the servo actuated step motion is proposed. A desktop miniature servo press machine, developed by Micro Manufacturing LLC., was used as a small motion controlling apparatus which is suitable for miniaturization of the process dimension. A small ultrasonic transducer with resonant frequency of 100kHz was used to incorporate the ultrasonic vibration system to a miniature servo press machine. A ultrasonic generator can track the resonant frequency automatically, which allows to keep amplitude during forming constant in the range of 100±10kHz. The punch made of SKD11 tool steel has a diameter of 4mm (Fig.2). The load cell is attached directly on the ultrasonic vibration transducer.

A micro-compression test of cylindrical specimens was carried out. As shown in Fig.3, the movement of the punch was regularly stopped during the forming process. The stress relaxation by step motion was started at the strain of 10% and repeated for 6 times with a constant strain interval of 3%. The relaxation time was fixed to 5s for every step. Ultrasonic vibration with amplitude of 1.2 and 2.4 μm was applied during the relaxation time. The specimens were compressed up to 0.4 nominal strain with an initial strain rate of $2 \times 10^{-2}$s$^{-1}$. To eliminate the influence of the friction, a powder graphite was used as the lubricant.

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Figure 1 Configuration of microforming system combining ultrasonic vibration and the servo actuated step motion, (a) Appearance of desktop miniature servo press machine and (b) Schematic illustration of micro-compression die assembly with ultrasonic vibration system.

Figure 2 Appearance of micro punch for a micro-compression test.
3. Experimental results

Figure 4 shows the true stress-true strain curves of compressed cylindrical brass in each size with and without combination of ultrasonic vibration. As shown in Fig.4, the stress drop increases with decreasing the specimen size. At the 4th of the step motion for the specimen with $\lambda =1$, the stress drop under the amplitude of 2.4$\mu$m changes significantly. This is because the resonant frequency of the specimen approaches the resonant frequency of the punch with decreasing the specimen size.

Figure 4 True stress-true strain curves for the specimen with different scale dimension, (a) True stress-true strain curves of the specimens with $\lambda =1$, (b) $\lambda =2$ and (c) $\lambda =4$. The true stress-true strain curves are plotted with the solid black line(without ultrasonic vibration), gray line(with ultrasonic vibration with amplitude of 1.2$\mu$m) and light gray line(with ultrasonic vibration with amplitude of 2.4$\mu$m), respectively. The stress drop by step motion increases with decreasing the specimen size.
Figure 5 summarizes the average value of the stress drop from the 1st to the 3rd step. In all process conditions, the stress drop increases with decreasing the specimen size. In the step motion with ultrasonic vibration, the stress drop increases with increasing the amplitude of ultrasonic vibration.

4. Discussion

To investigate the size dependency of the effect of ultrasonic vibration on stress relaxation by step motion, the stress drop in the surface and inner grains was calculated. Based on the surface grain theory (Lai, et al., 2008), the ratio of surface to total grains number $\eta$ can be calculated by the following equations.

\[
N_{\text{sur}} = \frac{S}{S_g} - \frac{2\pi D}{d} = \frac{\pi DH + 0.5\pi D^2}{0.25\pi d^2} - \frac{2\pi D}{d}
\]  

\[
N = \frac{\pi D^2 H}{4d^3}
\]  

\[
\eta = \frac{N_{\text{sur}}}{N}
\]

where, $N_{\text{sur}}$ is number of surface grains, $S$ is surface area of the specimen, $S_g$ is the exposed surface area of one grain, $D$ is diameter of the specimen, $H$ is height of the specimen, $d$ is diameter of one grain. By using ratio of surface to total grains number, the stress drop by combining ultrasonic vibration and step motion $\Delta \sigma_{\text{comb}}$ is divided into the stress drop of surface grains $\Delta \sigma_{\text{comb}}^s$ and inner grains $\Delta \sigma_{\text{comb}}^i$. The stress drop relaxation by ultrasonic vibration $\Delta \sigma_{\text{vib}}$ and step motion $\Delta \sigma_{\text{step}}$ is also expressed similarly as follows.

\[
\Delta \sigma_{\text{comb}} = \eta \Delta \sigma_{\text{comb}}^s + (1 - \eta) \Delta \sigma_{\text{comb}}^i
\]  

\[
\Delta \sigma_{\text{step}} = \eta \Delta \sigma_{\text{step}}^s + (1 - \eta) \Delta \sigma_{\text{step}}^i
\]  

\[
\Delta \sigma_{\text{vib}} = \Delta \sigma_{\text{comb}} - \Delta \sigma_{\text{step}} = \eta \Delta \sigma_{\text{vib}}^s + (1 - \eta) \Delta \sigma_{\text{vib}}^i
\]

In addition, $\Delta \sigma_{\text{comb}}^s$ and $\Delta \sigma_{\text{comb}}^i$ are expressed as the following equations.

\[
\Delta \sigma_{\text{comb}}^s = \Delta \sigma_{\text{step}}^s + \Delta \sigma_{\text{vib}}^s
\]
Here, the stress drop by step motion for the specimens with $\lambda=1$ and 2 is assumed as the same between the surface and inner grains. This is because the stress drop by step motion is relatively small compared with the stress drop by ultrasonic vibration. Therefore, $\Delta\sigma_{comb}^s$ and $\Delta\sigma_{comb}^i$ can be calculated from Eqs. (4)-(8). As shown in Fig. 6, the stress drop in the surface grains is larger than that in the inner grains in similar scale dimension. Additionally, the stress drop in the surface grains increases with decreasing the specimen size. According to Hung and Tsai (2013), the speed of dislocations is increased due to the absorption of ultrasonic energy. This suggests that the ultrasonic vibration promotes the diffusion of dislocations. Since the dislocations in the surface grains are less restricted than that in the inner grains, stress relaxation by ultrasonic vibration increases for the smaller specimen which has larger ratio of the surface grains to volume. Thus, ultrasonic vibration could contribute to improve the formability in micro scale.

$$\Delta\sigma_{comb}^i = \Delta\sigma_{step}^i + \sigma_{vib}^i$$  (8)

![Figure 6](image)

**Figure 6** The stress drop in the surface and inner grains, (a) The stress drop in the specimen with $\lambda=1$ and (b) $\lambda=2$.

Based on the surface grain theory, the stress drop in the surface and inner grains was calculated and plotted with blue bar (the stress drop in surface grains) and with red bar (the stress drop in inner grains). The stress drop in the surface grains is larger than that in the inner grains in similar scale dimension and increases with decreasing the specimen size.

5. Conclusion

The novel microforming process combining ultrasonic vibration and the servo actuated step motion was proposed. The effect of ultrasonic vibration on stress relaxation by step motion was investigated by a micro-compression test in different scale dimension. In the all process conditions, the stress drop increases with decreasing the specimen size. To investigate the size dependency of stress relaxation by ultrasonic vibration, the stress drop in the surface and inner grains was calculated. The stress drop in the surface grains is much larger than that in the inner grains in similar scale dimension. In addition, the stress drop in the surface grains increases with the decreasing the specimen size.

For the discussion of size dependency on this process, further investigation by numerical analysis considering the surface grain theory is required.

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References


