VARIATION OF PLASTIC STRAIN RATIOS OF $\alpha$-BRASS SHEET WITH TENSILE STRAIN

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(Received in final form 28 September 1997)

A study has been made of the changes in the instantaneous plastic strain ratios along various directions of $\alpha$-brass sheet as a function of tensile strain. The $\alpha$-brass sheet was fabricated by 88% cold rolling and subsequent annealing at 450°C for 1.5 h, which lead to complete recrystallization. The recrystallization texture of the $\alpha$-brass sheet could be approximated by $\{110\}\{110\}$. The plastic strain ratio along the rolling direction decreased with increasing tensile strain, whereas those along $45^\circ$, $90^\circ$ to the rolling direction were almost independent of tensile strain. The results were in agreement with those calculated using the recrystallization textures based on the Taylor–Bishop–Hill full constraints model.

Keywords: $\alpha$-brass; Instantaneous plastic strain ratio; Texture; Tensile strain; Taylor–Bishop–Hill theory; Full constraints model

1. INTRODUCTION

Variation of the plastic strain ratio or the Lankford parameter with tensile strain has been reported by many investigators (Hu, 1975a,b; Truzkowski, 1976; Arthey and Hutchinson, 1981; Liu, 1983). In order to understand the phenomenon, it is convenient to classify the plastic strain ratio into the conventional and instantaneous plastic strain ratios.

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The conventional plastic strain ratio, $R_e$, suggested by Lankford is defined by

$$R_e = \varepsilon_w / \varepsilon_t = -\varepsilon_w / (\varepsilon_t + \varepsilon_w) \quad (1)$$

where $\varepsilon_w$, $\varepsilon_t$ and $\varepsilon_l$ are the true plastic strains in the width, thickness and tensile directions, respectively. It is noted that no volume change in plastic deformation is assumed in Eq. (1). The $R_e$ value is usually calculated from the measured $\varepsilon_w$ and $\varepsilon_l$ values, and is widely used to evaluate deep drawability of sheet metals.

If the $R_e$ value is independent of tensile strain, the $\varepsilon_l - \varepsilon_w$ curve will show a linear relation as shown in Fig. 1, where the slope of line is given by $-R_e/(R_e + 1)$. If there is no error, the line must start from zero point. However, the measured $\varepsilon_l - \varepsilon_w$ results often show relations as in Fig. 2. The first case shows a linear relation of $\varepsilon_l - \varepsilon_w$ except in the initial stage, whereas the second case shows no linear relation at all. The first case may again be classified into two cases as shown in Fig. 3(a) and (b). For Fig. 3(a) and (b), $R_e$ will behave as shown in Fig. 3(c) and (d) as a function of tensile strain $\varepsilon_l$.

![FIGURE 1 Schematic drawing of width strain $\varepsilon_w$ as function of tensile strain $\varepsilon_l$ when plastic strain ratio $R$ is independent of strain.](image-url)
If the plastic strain ratio is defined by the instantaneous slope of the $\varepsilon_t-\varepsilon_w$ curve, the results in Fig. 3(a) and (b) will give rise to the curves $R_i$ in Fig. 3(c) and (d). For the second curve in Fig. 2, $R_e$ and $R_i$ are defined in Fig. 4 (Welch et al., 1983; Lake et al., 1988). $R_i$ is called the instantaneous plastic strain ratio and is expressed as

$$R_i = \frac{d\varepsilon_w}{d\varepsilon_t}. \tag{2}$$

The instantaneous plastic strain ratio corresponds to the quantity that is usually calculated from the texture.

The objective of this article is to measure the instantaneous plastic strain ratio of $\alpha$-brass sheet as a function of tensile strain and to discuss the results based on its textures.

2. EXPERIMENTAL METHOD

The 0.8 mm thick $\alpha$-brass sheet (Cu-28% Zn) was made by 88% cold rolling at room temperature, followed by annealing at 450°C for 1.5 h.
The tensile specimens of ASTM E8 subsize were prepared by milling the α-brass sheets.

The width and longitudinal displacements during tensile testing were instantaneously measured using two extensometers. The longitudinal displacement was measured up to 10 mm at intervals of 4.8 μm, while the width displacement was measured up to 1.5 mm at intervals of 0.69 μm, which is equivalent to about 1000 data at a tensile strain of 0.2. The measured displacements were used to calculate strains, from which the plastic strains were obtained by subtracting the elastic strains. The elastic strains were calculated using the following equation:

\[ \varepsilon_w^e = -\nu \varepsilon_l^e = \frac{\nu}{E} \sigma(\varepsilon_l) \]  

where superscript \( e \) represents elastic property, and \( \nu \) is Poisson’s ratio. Equation (3) holds for isotropic elastic materials. Therefore, the
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3. RESULTS AND DISCUSSION

Figure 5 shows the measured width strains and the $R_i$ values along $0^\circ$, $45^\circ$ and $90^\circ$ to the rolling direction of $\alpha$-brass specimens as a function of

\[ -q_e = \frac{-R_e}{R_e + 1} \]

\[ -q_i = \frac{R_i}{R_i + 1} \]

FIGURE 4 Definition of conventional plastic strain ratio $R_e$ and instantaneous plastic strain ratio $R_i$, where $-q_e$ and $-q_i$ are slopes of dashed and sold lines.

effect of elastic anisotropy on the plastic strains was neglected. Young’s modulus and Poisson’s ratio used are 115 GPa and 0.343, respectively.

In order to reduce the noise of the measured data, an instantaneous plastic strain ratio was calculated from the slope of a quadratic equation best fitting 50 data obtained from a tensile strain range of $\pm 0.5\%$.

The textures of the annealed specimens were measured up to the reflection angle of $80^\circ$ using a Schultz pole figure device. Incomplete pole figures of (111), (200) and (220) for the $\alpha$-brass specimen were used to calculate ODFs using the series expansion method with $L_{\text{max}} = 22$ (Bunge, 1982).

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tensile strain. The $R_i$ values of 45° and 90° specimens are independent of the tensile strain, whereas the $R_i$ values of 0° specimen decreases with increasing tensile strain.

Figure 6 shows the measured (111) and (200) pole figures of the annealed specimen. Figure 7 shows the measured (111) and (200) pole
FIGURE 6  Measured (111) and (200) pole figures of annealed α-brass sheet.

FIGURE 7  Measured (111) and (200) pole figures of α-brass sheet tensile deformed by 33%.

figures of the specimen tensile deformed by 33% along the rolling direction. The ODFs calculated using the pole figures in Figs. 6 and 7 are shown in Fig. 8(a) and (b), respectively. The texture of the annealed specimen may be approximated by the $\{110\}\langle110\rangle$ orientation and the texture of the tensile deformed specimen may be approximated by the $\{110\}\langle111\rangle$ orientation.
The $R_i$ values of the annealed and tensile deformed specimens were calculated as a function of angle to the rolling direction using Bunge’s method (Bunge, 1982) based on the measured textures (Fig. 9). The calculated $R_i$ values of the annealed specimen along 0°, 45° and 90° to the rolling direction are 1.60, 0.86 and 0.46, respectively, which are in good agreement with the measured $R_i$ values at the small tensile strain (Fig. 5(b)). The calculated $R_i$ values of the tensile deformed specimens
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FIGURE 9 Instantaneous plastic strain ratio calculated using Bunge's method as function of angle to rolling direction for annealed and tensile deformed α-brass sheet.

along 45° and 90° to the rolling direction are similar to those of the annealed specimens, whereas the $R_i$ value along the rolling direction decreases drastically. This decrease of $R_i$ value along the rolling direction was attributed to the observed texture change from \{110\}〈110〉 to \{110\}〈111〉.

For qualitative understanding of the $R_i$ results, the development of texture was calculated as a function of tensile strain, from which the $R_i$ was calculated. The annealing texture of α-brass sheet was expressed as the Gaussian function of \{110\}〈110〉 orientation with a half width of 30° and the calculated pole figures and ODF are shown in Figs. 10 and 11(a), respectively. Therefore, the annealing texture of 45° and 90° specimens was expressed as Gaussian functions of \{110\}〈11\sqrt{2}〉 and \{110\}〈001〉 orientations with a half width of 30°.

The tensile deformation textures were calculated using the Taylor–Bishop–Hill full constraints model, in which the slip systems were
FIGURE 10 (111) and (200) pole figures of \{110\}(110) texture expressed as Gaussian function with $L_{\text{max}} = 22$ and $\omega_0 = 30^\circ$.

SELECTED USING THE RANDOM CHOICE OF LINEAR PROGRAMMING METHOD (VAN HOUTTE, 1981). THE CALCULATED DEFORMATION TEXTURES ARE SHOWN IN FIGS. 11–13. THE \{110\}(110) AND \{110\}(111) orientation of 0° and 45° specimens are rotated to \{110\}(111) orientation during tensile deformation, while the \{110\}(001) orientation of 90° specimen is stable. The calculated annealing and deformation textures were used to calculate the $R_i$ values using Bunge's method. The calculated results are shown in Fig. 14. It can be seen that the 0° specimen of \{110\}(110) orientation yields $R_i$ values which strongly decrease with increasing tensile strains, whereas
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FIGURE 12  ODFs at $\varphi_2 = 0^\circ$ section of $\alpha$-brass sheet tensile deformed along $45^\circ$ to rolling direction, which were calculated using Taylor–Bishop–Hill full constraint model. (a) $\varepsilon_1 = 0.0$, (b) $\varepsilon_1 = 0.4$, (c) $\varepsilon_1 = 1.5$.

FIGURE 13  ODFs at $\varphi_2 = 0^\circ$ section of $\alpha$-brass sheet tensile deformed along $90^\circ$ to rolling direction, which were calculated using Taylor–Bishop–Hill full constraint model. (a) $\varepsilon_1 = 0.0$, (b) $\varepsilon_1 = 0.4$, (c) $\varepsilon_1 = 1.5$.

the $R$ values of the $45^\circ$ and $90^\circ$ specimens are virtually independent of the tensile strain.

These results are in qualitative agreement with the measured $R_i$ values. Therefore, the variations of $R_i$ with tensile strain can be attributed to the texture change in $\alpha$-brass sheets during tensile deformation.

4. CONCLUSION

The instantaneous plastic strain ratios and textures of $\alpha$-brass sheets were measured as functions of tensile strain and angle to the rolling
direction. The recrystallization texture of α-brass sheet rolled by 88% and annealed at 450°C for 1.5 h was approximated by \( \{110\langle110\rangle \), which changed to the texture approximated by \( \{110\langle111\rangle \) after a tensile strain of 33%. The \( R_i \) values of specimens along 45° and 90° to the rolling direction were almost independent of tensile strain, whereas that of the 0° specimen decreased with increasing tensile strain. The \( R_i \) results are attributed to the texture variation during tensile deformation.

**Acknowledgments**

This study has been supported by Korea Science and Engineering Foundation through RETCAM, Seoul National University.

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