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INFLUENCE OF TWO STAGE STRAIN PATH ON FORMING LIMIT STRAINS AND TEXTURE IN ALUMINUM SHEET

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Abstract

The influence of the two types of two stage strain paths; (1) uniaxial tensile straining followed by orthogonal tensile straining and (2) equibiaxial tensile straining followed by uniaxial tensile straining, on the forming limit strains in aluminum sheet has been investigated. The texture change corresponding to the two stage strain paths has been also studied.
The strain path-1 yields the reduced forming limit strains compared to the forming limit curve determined with single stage strain path. The strain path-2 yields the decreased forming limit strains in the region near to equibiaxial deformation and increased forming limit strains in the regions of plane strain deformation and uniaxial tensile deformation. These influences of two stage straining on the forming limit strains are due to the accumulation or relaxation of strains in the sheet. When the new texture is developed in the sheet by the primary straining, the effect of the two stage straining becomes notable.

Introduction

It is known that the stress-strain relationship is affected by the previous deformation, when metallic materials are deformed with the two stage deformation [1]. In the forming processes of metallic materials, various modes of deformations or their combinations are applied. In some cases, the previous deformation yields the effect to increase the forming limit strains in the subsequent forming process. The formability of sheet materials can be assessed with the forming limit diagram (FLD) [2] [3], in which the strains are represented in the direction of the largest principal surface strain and the direction perpendicular to it. The combination of two different modes of deformations can be shown as a two stage strain path on a forming limit diagram. By selecting a proper strain path, increased forming limit strains without failure can be achieved. In two stage straining of sheet materials, texture in the sheet should be affected by the strain path. Little has been reported on the texture changes in the two stage straining.

In the present study, the influence of the primary deformation on the forming limit strains in the subsequent deformation in two stage straining of aluminum sheet was investigated. Two types of two stage strain paths; (1) combination of orthogonal uniaxial tensile strainings and (2) combination of biaxial tensile straining and uniaxial tensile straining, were tested. The texture change in the sheet corresponding to the two stage straining was also studied.

Experimental

Aluminum sheets (AA1050-O) of 1 mm thickness were used in the present study. Two types of two stage deformations of the sheets were carried out by the following procedures.

(1) Strain path-1; Uniaxial tensile straining followed by orthogonal uniaxial tensile straining. Rectangular sheets of 200 x 400 mm were uniaxially stretched with elongations of 5-15 % as the primary straining using a tensile testing machine and wide specimen holders. Since the aluminum sheets have the anisotropy in mechanical properties, the direction of the primary stretching was aligned to the rolling direction of the original sheet to keep the fixed relation between the primary and the secondary straining. The test pieces were blanked from the central portion of the stretched sheets at right angle to the direction of the primary stretching. Then, the test pieces were stretched with a tensile testing machine as the secondary straining.

(2) Strain path-2; Equibiaxial tensile straining followed by uniaxial tensile straining. Circular blanks of 160 mm diameter were prepared by blanking from the original sheets. The blanks were hydraulically bulged as the primary straining to various heights with a bulging machine. The tensile test pieces were cut from the bulged cups by machining. The test pieces were stretched as the secondary straining with a tensile testing machine. To hold the fixed directional relations between the strain path-1 and the strain path-2, the longitudinal direction of tensile test piece was aligned to the rolling direction of the original sheet.

The strains in the forming limit diagram in the present study were defined as follows. The major strain is parallel to the rolling direction and the minor strain is parallel to the transverse direction of the original sheet. The directional relations between the primary and the secondary straining in the strain path-1 and the strain path-2 and between the major and the minor strain are illustrated in Fig. 1.

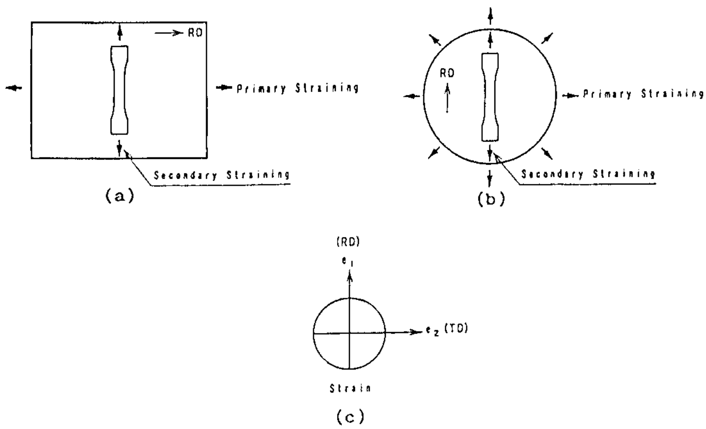

Fig. 1 Relations between the primary and the secondary stage deformation in Strain path-1 (a) and Strain path-2 (b). Directions of the strains (c).

The details of the experimental procedure for determining the forming limit diagram with the single stage and the two stage strain path deformation are described elsewhere [4] [5] . The local strains were determined with a circular grid of 2.5 mm diameter printed on the surface of test pieces. The strains are represented with the conventional strain in the text unless otherwise mentioned.
The pole figures of the test pieces after straining were determined with the reflection and the transmission method only for the specimens having the size large enough for texture determination.

Results

The change in strain in the test piece during the two stage straining along the strain path-1 is shown in Fig. 2, together with the changes in strain in uniaxial tensile deformations in the rolling and the transverse direction. The forming limit curve determined with a single stage deformation is also shown with dotted line in Fig. 2. The curves for the second stage deformation with different primary strains are almost parallel to the curve of single stage deformation in the trasverse direction. However, the forming limit strains in the two stage tensile straining are less than those in the single stage straining. Within the limits of this experiment, the larger the primary strain, the larger the decrease in the forming limit strains.

The effect of the two stage strain path-2 on the forming limit strains is shown in Fig. 3. Compared to the forming limit curve determined with single stage strain path, the forming limit strains decrease in the region near to equibiaxial tensile dedformation ($e_1 = e_2$), but increase in the regions of plane strain deformation ($e_2 = 0$) and uniaxial tensile deformation ($e_2 < 0$). Especially, the increase of forming limit strains is remarkable in the region near to plane strain deformation.

The texture change corresponding to the strain path-1 is shown in Fig. 4. The pole figure of the original sheet (A) shows the typical annealing texture of rolled aluminum sheet having the components of cube and R orientations. After the primary straining, the texture is similar to that of original sheet, but the strong components are weakened (B). After the secondary straining, the components are further weakened (C). The texture change corresponding to the strain path-2 is shown in Fig. 5. In this case, the pole figures after the secondary straining were not deteremined, because the size (width) of test

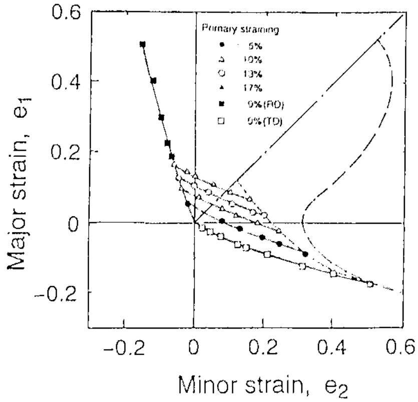

Fig. 2 Forming limit strains with Strain path-1.

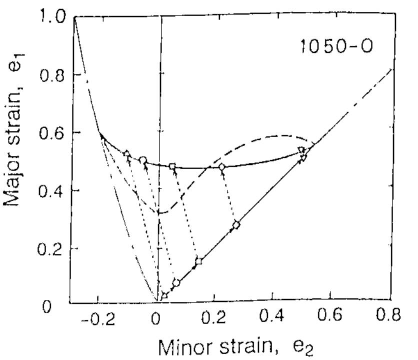

Fig. 3 Forming limit strains with Strain path-2.

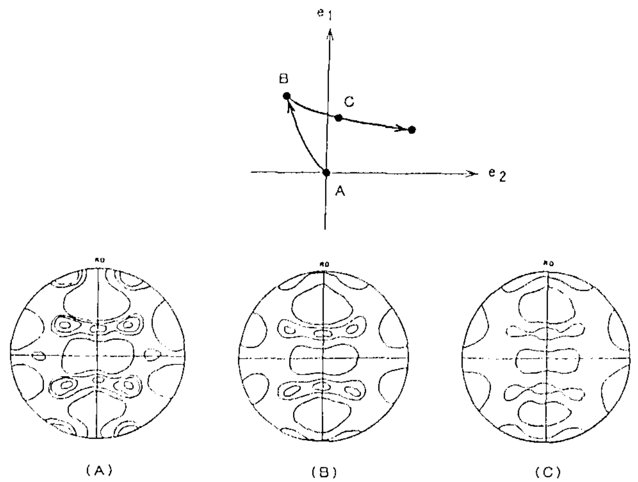

Fig. 4 (111) pole figures of aluminum deformed with Strain path-1.

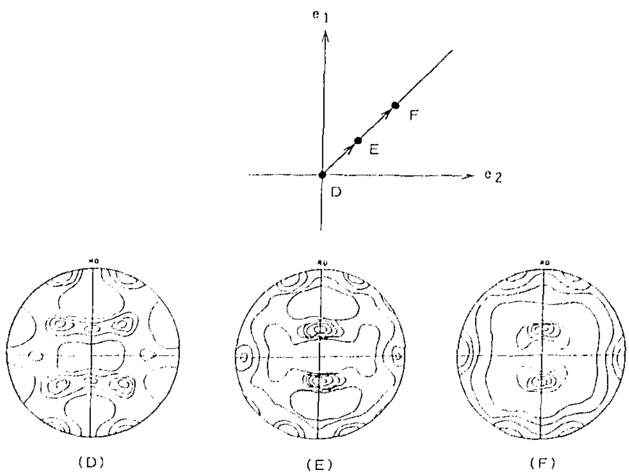

Fig. 5 (111) pole figures of aluminum deformed with the primary stage of Strain path-2.

pieces were small and hard to determine the pole figure. The texture of the original sheet (D) changes to the texture with the ring like distribution of poles showing that the component is ⟨110⟩ axes parallel to the normal of rolling plane (E),(F) [8] .

Discussion

In uniaxial tensile deformation, a specimen is elongated in the direction of tensile axis, but contracted in the transverse direction. Accordingly, it is expected that the prestraining has an effect of strain relaxation for the subsequent straining in the orthogonal tensile strain path.
However, the prestraining in the strain path-1 yields the reduced forming limit strains compared to those in single stage strain path. Lloyd and Sang [6] reported that the prestraining of aluminum and aluminum alloys resulted in the reduced residual strain in the subsequent orthogonal tensile straining except an Al-Fe-Ni alloy. This means that the strains were not relaxed, but accumulated in the sheet deformed with orthogonal strain path contrarily to the expectation in the macroscopic scale.
Little has been reported about the effect of the biaxial tensile prestraining on the plastic behavior in the subsequent uniaxial tensile straining. Sang and Lloyd [7] reported that the biaxial prestraining resulted in the reduced hardening in the subsequent uniaxial tensile straining. However, the limit strains were not compared with the the FLD in their report [7] . As shown in Fig. 4, the forming limit strains by the two stage straining decrease in the region near to equibiaxial deformation, but increase in the regions of plane strain deformation and uniaxial tensile deformation compared to the forming limit curve by the single stage deformation. Since the strains in the highly bulged sheet are near to the fracture limit, the addition of any type of strain would result in fracture of the sheet. So, the limit strains by the two stage s training are reduced in the region near to equibiaxial deformation. However, there should be some margin for the addition of strain inthe sheet bulged to the lower height. If the secondary straining has the effectto relax the strain due to the prestraining, the forming limit strains would be increased. The reason why the forming limit strains are remarkably increased, especially in the region of plane strain deformation is not clear at present.
The texture change in the orthogonal tensile strain path shows that the strong pole concentrations in the original sheet are weakened during the two stage strainig, but the texture of the sheet is considered to be the retained original texture. Since the primary tensile deformation in the present study was not large enough to develope the new texture in the sheet, the compensation of

strains between the primary and the secondary straining would not occur. The texture of equibiaxially stretched sheet is represented as ⟨110⟩ axes parallel to the normal to the rolling plane. This orientation is suitable for the slip in the tensile deformation in any direction on the rolling plane. It may cause the strain relaxation in the sheet stretched in all directions on the rolling plane. However, the changes in the forming limit strains due to the two stage straining can not be adequately explained with the texture changes. Further work on the microstructural change in the sheet is required to understand the mechanism of strain relaxation in the two stage straining.

Summary

The present investigation on the influence of two stage strain path on the forming limit strains and texture in aluminum sheets are summarized as follows.

(1) Uniaxial tensile straining followed by orthogonal uniaxial tensile straining decreases the forming limit strains.

(2) Equibiaxial tensile straining followed by uniaxial straining decreases the forming limit strains in the region near to equibiaxial tensile deformation, but increases the forming limit strains in the regions of plane strain deformation and uniaxial tensile deformation. Especially the increase in the forming limit strains in the region near to plane strain deformation is remarkable.

(3) The texture of aluminum sheet changes correspondingly to the two satage strain path. When the new texture is developed in the sheet by the primary straining, the effect of the compensation of strains becomes notable.

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