NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 3439

ANALYSIS OF EAR FORMATION IN DEEP-DRAWN CUPS

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SUMMARY

A review of the literature on deep drawing and on anisotropy of metals indicates that no direct correlation has been established between the number and location of the ears on deep-drawn cups and the preferred crystallographic orientation of the blank material. In the present paper, a method for predicting earing behavior is proposed which is based on the plastic properties of single crystals and a knowledge of the preferred orientation of the blank material. The proposed method of prediction is in satisfactory agreement with reported experimental results.

INTRODUCTION

In order to understand the gross deformational behavior of polycrystalline metals, a knowledge of the deformational characteristics of the grains themselves is necessary. An example of the effect of the individual grains on the behavior of the metal as a whole is exhibited by the formation of ears in the deep-drawing process. This process is widely used in the manufacture of many intricately shaped aircraft components, and a simple example of it is the forming of a thin, circular blank into a cylindrical cup as indicated in figure 1. The blank material is usually taken from rolled sheet, which often possesses preferred crystallographic orientation associated with the processing history of the sheet. This preferred orientation may be highly objectionable since it may lead to the formation of ears around the rim of the cup and to variations in side-wall thickness. A typical example of ear formation is shown in figure 2.

In the past, attempts have been made to correlate ear formation with the mechanical properties of the blank, but none have been universally successful. General reviews of these works may be found in references 1 and 2. More recently, Bourne and Hill (ref. 3) developed a theoretical method for correlating certain material constants with the number and location of ears. These constants define the state of anisotropy of the blank and must be found by test.

Although these past investigations have demonstrated that ear formation is associated with preferred orientation, no method for correlating ear formation directly with crystallographic orientation has been developed. The purpose of this paper is to show that the number and location of ears can be computed on the basis of single-crystal behavior and a knowledge of the orientation of the polycrystalline aggregate. No experimental determination of the properties of the sheet, as in reference 3, is required. Although the proposed method is a general one, only face-centered cubic metals are considered in this paper.

SYMBOLS

ϵ_c	circumferential strain
ϵ_r	radial strain
$l_{1c}, l_{2c}, l_{1r}, l_{2r}$	direction cosines
α	angle between radial and rolling directions
γ	shear strain

THEORY

In order to simplify the analysis of the deep-drawing process, assumptions similar to those of Bourne and Hill (ref. 3) are adopted. These assumptions are as follows:

(1) Ear formation depends mainly on conditions near the rim, where the state of stress is essentially a pure circumferential compression.

(2) Each element of the rim is subjected to the same circumferential strain.

(3) The blank-holder pressure is negligible; thus, there exists a state of uniaxial plane stress.

In addition, the following assumptions are made with respect to the material of the blank:

(4) Slip is the mechanism of plastic deformation.

(5) The state of anisotropy remains essentially unchanged during the drawing process.

(6) The circumferential strain of a small element is the same as that of each grain in the element.

(7) In each element, the radial strain is the average of the radial strains of the individual grains of the element.

A set of assumptions equivalent to assumptions (4), (5), (6), and (7) were employed with reasonable success for the determination of Poisson's ratio in the plastic range (ref. 4). Consequently, for the present case which also involves the determination of plastic strains, these assumptions are expected to be fairly reliable.

Consider a grain in an element near the rim of the blank at an intermediate stage of the deep-drawing process. The circumferential strain in the grain ϵ_c is related to the shearing strain due to slip in the active slip system by the following expression:

$$\epsilon_c = l_{1c} l_{2c} \gamma \tag{1}$$

The quantity γ is the shear strain in the slip system, l_{1c} is the direction cosine between the circumferential direction and the slip-plane normal, and l_{2c} is the direction cosine between the circumferential direction and the slip direction. The operative combination of slip plane and slip direction for any arbitrary grain orientation is shown in figure 15 of reference 4 for face-centered cubic metals.

The radial strain in the grain ϵ_r is given by

$$\epsilon_r = l_{1r} l_{2r} \gamma \tag{2}$$

where l_{1r} is the direction cosine between the radial direction and the slip-plane normal and l_{2r} is the direction cosine between the radial direction and the slip direction.

Inasmuch as ϵ_c is a constant (see assumption (6)), then, after γ has been eliminated the following relationship between ϵ_r and ϵ_c is obtained:

$$\frac{\epsilon_r}{\epsilon_c} = \frac{l_{1r} l_{2r}}{l_{1c} l_{2c}} \tag{3}$$

When all the grains of the element are similarly oriented, equation (3) is applicable without modification. When two or more orientations are present, a weighted average value of the radial strain must be determined in accordance with assumption (7). Whenever a texture is made up of twin components, each component must be treated as a distinct orientation.

Since ϵ_c is a constant, a plot of the variation of ϵ_r/ϵ_c against α, the angular position around the periphery of the cup measured from the rolling direction, will indicate the type of ear formation to be expected; wherever ϵ_r/ϵ_c is a maximum, an ear will be formed. A number of cases have been investigated and are discussed in the next section.

RESULTS

Several distinct types of earing behavior have been reported in the literature, and the following examples are intended to cover the range of this behavior and to demonstrate the validity of the proposed method. Only cases for which the orientation was definitely established or for which pole figures were available are considered.

Baldwin, Howald, and Ross (ref. 5) tested recrystallized copper which possessed a high percentage of cubically alined grains. They reported that ears developed at the 0° and 90° positions to the rolling direction. Aust and Morral (ref. 6) obtained similar results with cubically alined 1100 (2S) aluminum. For comparison with these findings, the solid curve of figure 3(a) has been computed with the assumption that all the grains are cubically alined. The dashed curve has been calculated by assuming a spread of 10° about the ideal orientation. The theory predicts that ears should form at the 0° and 90° positions where ϵ_r is a maximum; this prediction is in accord with the experimental results.

Burghoff and Bohlen (ref. 7) investigated the earing behavior of 68-32 brass strip. For material which had been rolled 84 percent and annealed at 425° C and then rolled 50 percent and annealed at 650° C, ears were formed at the 45° positions to the rolling direction. It appears from the (111) pole figure for this material (fig. 9 of ref. 7) that the texture may be described by the following orientations: $(110)[1\bar{1}2]$, $(110)[\bar{1}12]$, and $(1\bar{1}2)[\bar{1}11]$ which are in the proportions of 25%, 25%, and 50%, respectively. A theoretical curve has been computed on this basis and is presented in figure 3(b) together with a faired curve which is intended to approximate the behavior of the actual material. A single maximum value for ϵ_r occurs near the 45° position and this value is in agreement with the experimental findings.

Burghoff and Bohlen (ref. 7) have also obtained cups with ears at the 0° and 60° positions. The material was also 68-32 brass which was rolled 50 percent and annealed at 565° C and then rolled 85 percent and annealed at 650° C. It appears from the (111) pole figure for this case (fig. 10 of ref. 7) that the texture centered about the $(110)[3\bar{3}7]$ and the $(110)[\bar{3}37]$ orientations with equal amounts of each orientation present. The theoretical and faired curves for this case are shown in figure 3(c). The maximum values of ϵ_r occur at the 0° and 60° positions; this result again is in accord with the experimental results.

CONCLUDING REMARKS

Three different cases of earing behavior have been investigated, and in all cases the present theory has been found to be in agreement with the experimental results. This satisfactory correlation shows that the anisotropy of plastic flow due to the crystalline nature of the material is responsible for ear formation. In addition, the assumptions made concerning the deep-drawing process and the nature of the deformation of the polycrystalline aggregate are also substantiated by this satisfactory correlation.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., February 9, 1955.

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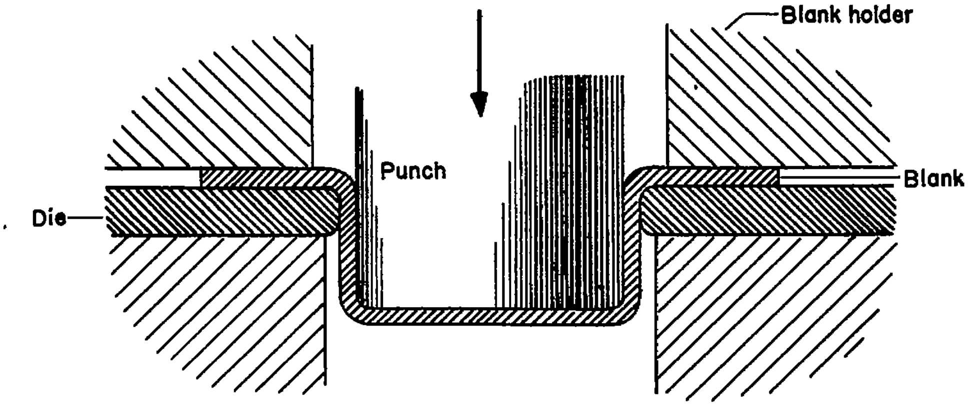
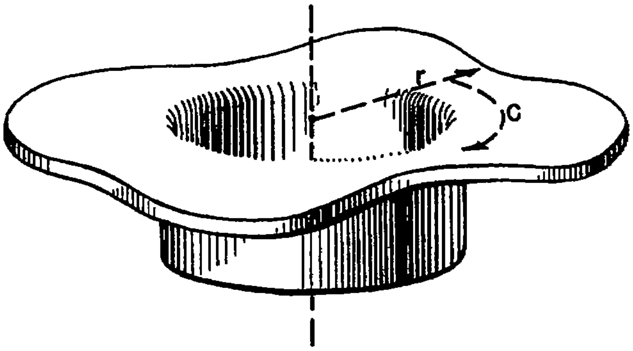
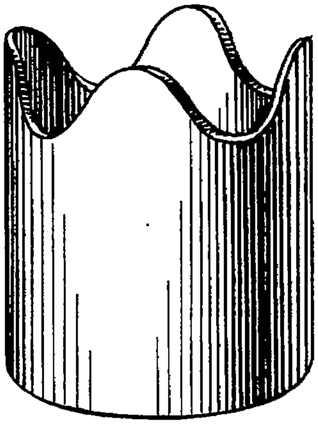


Figure 1.- Deep drawing of a circular blank into a cylindrical cup.

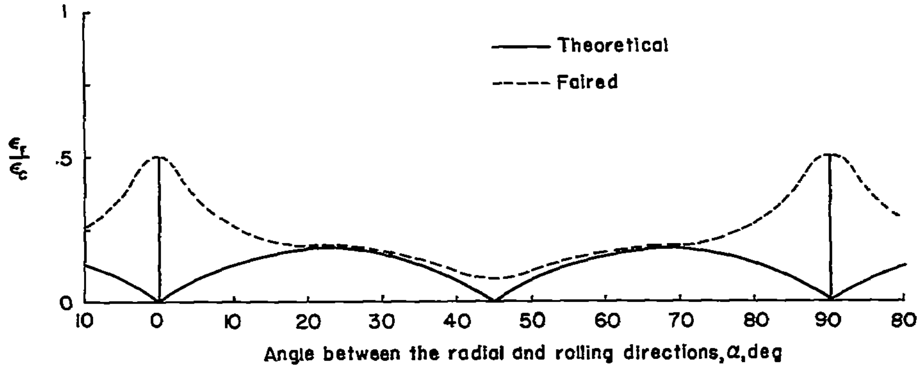


(a) Intermediate stage.

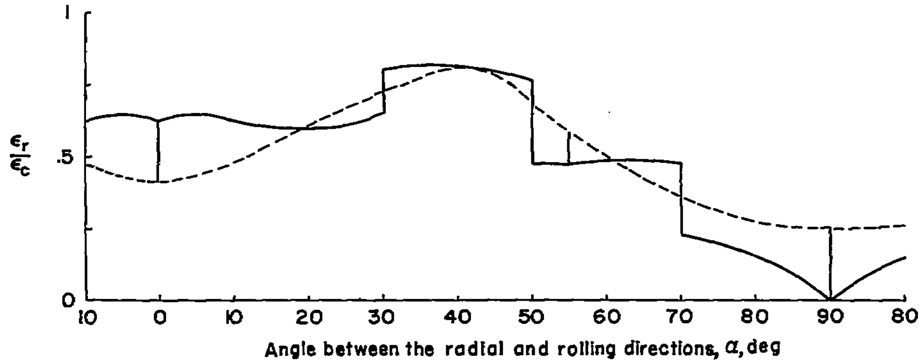


(b) Final stage.

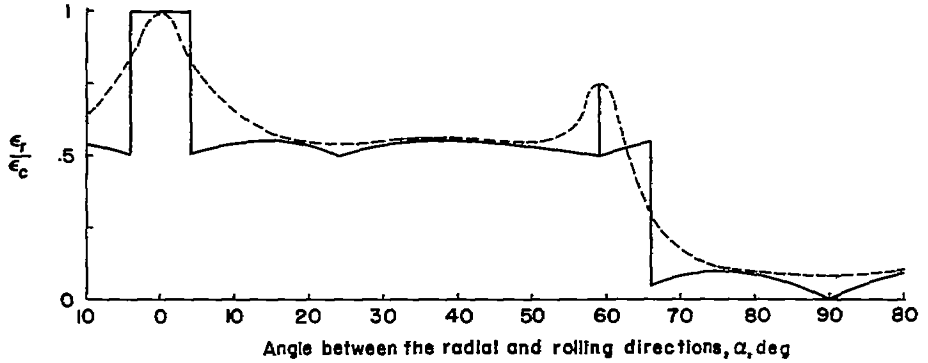
Figure 2.- An example of directional earing in a deep-drawn cup.



(a) (100)[001] orientation.



(b) Orientations of (110)[1$\bar{1}$2], (110)[$\bar{1}$12], and (1$\bar{1}$2)[$\bar{1}$11] which are in the proportions 25%, 25%, and 50%, respectively.



(c) (110)[3$\bar{3}$7] and (110)[$\bar{3}$37] orientations present in equal amounts.

Figure 3.- Variation of radial strain in deep-drawn cups possessing different preferred orientations.

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