ULTRASONIC MEASUREMENT OF THE EARING BEHAVIOR OF ALUMINUM PLATE

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INTRODUCTION

Material processing such as rolling most certainly introduces a preferred orientation (or texture) in the material. This anisotropy in mechanical properties has an important effect on the fabricability of the metal. For example, when drawing a cylindrical metal sheet, ears are formed around the top edge of the drawn sheet as shown in Fig. 1. These ears result from the sheet metal being stronger in one direction than in other directions in the plane of the sheet. This is also referred to as planar anisotropy which causes different deformations in various directions. In order to assure the quality of the product and to improve the manufacturing process, an effective way of measuring crystallographic texture has been sought for decades.

The most straightforward method to evaluate the earing behavior of a metal sheet is the cup-drawing test. This method is widely adopted by the aluminum industry. Generally, a commercially available drawing machine is used to draw cups 33 mm in diameter. The percent earing is determined by

\[
\text{percent earing} = \frac{h_p - h_v}{h_v} \times 100
\]

where \(h_p\) and \(h_v\) are the average heights of peaks and valleys, respectively. A device is also available to physically measure the percent earing from the drawn cups. The device is usually designed for use on cups which have four ears that are exactly 90° apart. However, it is not uncommon for a cup to have two, six or eight ears.

The other drawback of the cup drawing method is that the test is very operator sensitive. Several different variables exist that can cause different earing results. Some of these are the hold down (or clamping) force, the clearance between the punch and the die, the type of lubricant, and the die entry radius. In order to get repeatable results, very close attention must be paid to all variables.

Several other techniques are available to evaluate the material anisotropy, such as X-ray pole figure, neutron diffraction, r-value,
etc. These techniques are either cumbersome, unreliable, or present radiation hazards and are not suitable for routine industrial applications. There is a need to have a technique which is reliable, operator-independent, convenient and safe.

It has been known for some time that crystallographic texture affects the propagation of ultrasonic waves in a material. For an anisotropic material, the elastic moduli are not constant. They depend on the stress and strain directions. Since the elastic wave is directly related to the elastic modulus, the anisotropy of the material can be obtained by examining the wave velocities in different directions. This basic principal has been known for more than two decades [1]. The idea of using elastic moduli to predict the plastic-strain-ratio was suggested by Stickels and Mould in 1970 [2]. The relation between plastic-strain-ratio and degree of earing was reported even earlier by Wilson et al. [3]. These relations (ultrasonic wave velocities versus elastic moduli, elastic moduli versus plastic-strain-ratio, and plastic-strain-ratio versus earing) raise the possibility of evaluating the earing behavior by measuring ultrasonic wave velocities.

Recently, several studies have evaluated the ODC’s (orientation distribution constants) by using an ultrasonic technique. The results compared favorably with the texture measurements made with x-rays [4], neutron diffraction and destructive r-value tests [5]. The ODC’s are also known to be related to the earing behavior of the material [4, 6].

Although the earing behavior of a metal sheet can be linked to the ultrasonic wave velocities, the direct relation between the two has not been studied. The ultrasonic method may offer an alternative to the cup-drawing test. The nondestructive nature of the method makes it even more attractive. It can be used in on-line applications.

The purpose of this paper is to investigate the correlation between the ultrasonic velocities and the earing propensity of aluminum alloy AA3004 sheet.

THEORETICAL BACKGROUND

Consider a solid which has orthorhombic symmetry and is composed of cubic crystallites. Rolled thick plate may belong to this category. The coordinate axes coincide with the material symmetry axes. As shown in Fig. 2, the x-axis is along the rolling direction (RD), the y-axis is along the transverse direction and the z-axis is along the normal direction (ND). Let us further assume that the plate has weak anisotropy and is absent of stress. For an ultrasonic wave which is
polarized in the \((\sin \theta, \cos \theta, 0)\) direction and propagates in the 
\((\cos \theta, \sin \theta, 0)\) direction, Sayer [7, 8] derived the following relation

\[
p v^2(\theta) = \mu + \frac{4\sqrt{2}m^2}{35} c(\nu_{400} - \sqrt{70}\nu_{440}) + \frac{64m^2}{\sqrt{35}} c\nu_{440}\cos^2 \theta (1 - \cos^2 \theta)
\]  

(2)

where \(p\) is density, \(\mu\) is the isotropic shear modulus of the material, \(c\) is some constant related to elastic constants and \(\nu_{ims}\) is orientation distribution coefficient. The material motion (polarization) is parallel to the surface; this is known as a horizontally polarized shear wave (SH).

The result has been generalized to guided waves in thin plates (i.e. the plate thickness is small compared to ultrasonic wave length) by Thompson et al. [9, 10] which has the form

\[
p v^2(\theta) = A + BW_{400} + CW_{440}\cos \theta + DW_{440}\cos 2\theta.
\]  

(3)

The equation is valid for both the fundamental shear horizontal mode \((SH_0)\) and the Lamb wave mode \((S_0)\). (The material motion in \(S_0\) mode is parallel to the direction of propagation.) Here \(A, B, C,\) and \(D\) are constants and depend on the elastic moduli of the cubic crystals; their values depend on the particular wave mode.

Based on a new constitutive equation, an acoustoelastic theory has been developed by Man and Lu [11, 12]. For a class of monoclinic media that are almost transversely-isotropic, the speed of the quasishear wave has been shown, to the first order, to have the form

\[
u_{3\theta_0}(\theta) = \alpha_1 + \alpha_2 \sin^2 \theta + \alpha_3 \sin^2 \theta \cos^2 \theta + \alpha_4 \sin 2\theta + \alpha_5 \sin 2\theta \cos 2\theta.
\]  

(4)

Here the constants \(\alpha_1, \alpha_2\) and \(\alpha_5\) depend on both texture and stress, while \(\alpha_2\) and \(\alpha_4\) depend on stress only. Since orthotropic material is included in the monoclinic material, Eq. (4) is consistent with Eqs. (2) and (3) for the case that the material is stress free. In Man and Lu’s approach, the choice of \(x\)- and \(y\)-axes in the \(z = 0\) plane is arbitrary. This has the advantage that it is not necessary to know the material symmetry axes beforehand. They can be determined from measurement. If the \(x\)-axis is chosen to be aligned with one of the material symmetry axes, then \(\alpha_5 = 0\).
Davies et al. [6] noted that ODC $W_{440}$ controls the tendency to form four ears. When the coordinate axes coincide with the material symmetry axes and stress free, the information about $W_{440}$ can be obtained from two velocities $V_{SH}(0^\circ)$ and $V_{SH}(45^\circ)$. In general, at least five velocities are required to obtain the values $\alpha_i (i=1,...,5)$. The principal value of $\alpha_3$, which is related to $W_{440}$, is calculated by

$$\hat{\alpha}_3 = \alpha_3 \cos 4\Omega - 4\alpha_5 \sin 4\Omega \quad \text{where} \quad \tan 4\Omega = -\frac{4\alpha_5}{\alpha_3}$$

where $\Omega$ is the angle between the x-axis and the material symmetric axis.

**EXPERIMENT**

Three groups of aluminum alloy AA3004 specimens were tested. The specimens of the first two groups were prepared as follows. The hot band plates, about 0.1" in thickness, were heat treated at 645 °F for four hours. Then the plates were cold rolled to nine different thicknesses. Each specimen was identified with the reduction ratio, they were 0%, 25%, 50%, 65%, 70%, 75%, 80%, 83%, and 90%, respectively. For the specimen with 90% reduction ratio the thickness was 0.01". There was a subtle difference in the heat treatment between these two groups. The plates were stacked in the oven for the first group; the plates were separated from each other for the second group. The specimens of the third group had the same thickness 0.1", but were heat treated at different temperatures ranging from 200 °F to 1100°F. A total of 33 specimens were included in the three groups. All specimens had a size of 6"x6" and were prepared at the University of Kentucky.

The procedure of ultrasonic measurement was identical for all specimens. The velocities of 40 different directions, $0^\circ$, $5^\circ$, $15^\circ$, $30^\circ$, $40^\circ$, $45^\circ$, ..., were measured. After one cycle, the measurement was repeated in the reverse order. That is a total of 80 velocity measurements were taken for each specimen. (The detail of the experimental setup and velocity measurement is described in [13, 14].) By using a least-squares curve fitting method, the values of $\alpha_i (i=1,...,5)$ in Eq. (4) were obtained from the velocity data. The principal value of $\alpha_3$ of the specimen was then determined from Eq. (5). Just for simplicity, from now on $\alpha_3$ replaces $\hat{\alpha}_3$ to indicate the principal value.

After ultrasonic measurement, the percent earing of the specimens were determined from the conventional cup-drawing test. Only one cup was drawn from each specimen.

**RESULTS AND DISCUSSION**

The results of the ultrasonic measurement and the cup-drawing test of groups 1 - 3 are shown in Figs. 3 - 5, respectively. Positive degrees of earing indicate 90° ears, i.e. the four ears are located in $0^\circ$, $90^\circ$, $180^\circ$, and $270^\circ$ positions; negative earing means 45° ears. For ultrasonic results, the variable is $-\alpha_3$. Comparing the results of these two methods, $-\alpha_3$ and degree of earing, the exact same trend is observed.

The results of groups 1 and 2 are especially interesting. Since the plates to make group 1 specimens were stacked in the oven, the results of the heat treatment of these plates were not identical. The heat treatment of the plates to make group 2 specimens were uniform.
Fig. 3. Experimental results of group 1 specimens, (a) ultrasonic measurement, (b) percent earing from cup-drawing test.

Fig. 4. Experimental results of group 2 specimens, (a) ultrasonic measurement, (b) percent earing from cup-drawing test.

Fig. 5. Experimental results of group 3 specimens, (a) ultrasonic measurement, (b) percent earing from cup-drawing test.
Although the difference in heat treatment is subtle, the difference in earring behavior is quite significant. Fig. 4(b) shows a typical earring curve, while the data pattern in Fig. 3(b) is almost random. Ultrasonic results correlate with degree of earring very well.

Figure 6 shows exaggerated slowness curves for typical (a) 90° ears, and (b) 45° ears. The results indicate that the ears are located at faster $S_{H_0}$ speed.

All experimental data are plotted in Fig. 7. The correlation coefficient is 0.91 which suggests a strong correlation between these two methods. The comparison includes a wide variety of conditions:
different plate thicknesses, heat treatments, rolling processes, etc. The data are scattered within the two dashed lines which may be considered as an error band. Based on these data, the error is approximately ±1% which may seem large. However, it is very difficult to assess the accuracy of the ultrasonic prediction since the mechanical earing test has considerable uncertainty in its results as discussed earlier. The mechanical earing results are based on one reading per specimen which probably contributes to most of the scattering. Concerning the ultrasonic measurement, the flatness of the specimen influences the precision of the $\alpha_3$ value. Even though $\alpha_3$ is the most significant parameter, other parameters need to be included to improve the prediction.

The comparison is based on the four-ear case. When the absolute value of $\alpha_3$ is small, say $|\alpha_3|<1.5$ GPa, mixed ears (six or eight ears) may be observed on the drawn cup. In this case, the crystallographic texture is very weak and the sheet is very close to being isotropic. The influence of residual stress on ultrasonic wave velocities is relatively large compared to stronger texture cases. Similarly, in the cup-drawing test the operating condition may be more influential than the crystallite texture on the appearance of the ears.

In addition to the linear relation shown in Fig. 7, the data also suggest other relations between $\alpha_3$ and percent earing. For example, the 90° ear data appear to have a different relationship than the 45° ear data. The lines do not always pass through the origin. Obtainment of additional data will answer these questions.

Further analysis shows that generally it is not necessary to measure 80 velocities per specimen. For those cups with clearly four ears, eight (or even three) velocity measurements will be enough. More measurements are needed for sheets that have small or mixed ears.

CONCLUSIONS

The experimental data show a strong correlation between the parameter $\alpha_3$ and the percent earing of a drawn cup. The results demonstrate that ultrasonic velocities measure the earing propensity of aluminum alloy AA3004 sheets. The accuracy of the ultrasonic earing prediction is hard to determine since the cup drawing test is not precise. The ultrasonic method is operator-independent and nondestructive, which can be more effective for industrial applications.

REFERENCES