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Analysis of cup earing for AA3104-H19 aluminum alloy sheet

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ABSTRACT

A crystal plasticity based finite element model has been developed to simulate the earing in deep drawing. The crystallographic texture of a commercial can body alloy AA3014-H19 aluminum sheet has been analyzed by X-ray diffraction and electron back scatter diffraction (EBSD) techniques. The measured texture data were incorporated into the FE cup forming model, while the constitutive response at an integration point was described by the single crystal plasticity theory. It has been found that the initial texture and the spatial distributions of different texture components, which are determined by the re-roll texture after hot rolling and the subsequent cold rolling reduction, are the critical factors for earing. The earing is initiated at a very low strain during deep drawing and it intensifies with increasing draw without change of overall profile. The different earing types, i.e., Types-A, B and C, are likely be caused by the grain/texture band formed in the cold rolling process. While such banding becomes extensive due to the sheet thermo-mechanical processing, Types- B and C earing profiles are generated.

1. Introduction

The modern aluminum beverage can is made of two alloys: (i) Al-1Mn-1Mg (all in wt.%) AA3104 alloy for the can body, and (ii) Al-4.5Mg-0.3Mn AA5083 alloy for the can end and pull tub. The AA3104 sheet product for can body is supplied in the heavily cold rolled H19 temper. Commercial AA3104-H19 is fabricated through a carefully controlled thermo-mechanical processing route from direct chill (DC) casting, scalping, homogenization, hot rolling and cold rolling (Marshall, 1996). An industry-sized AA3104 ingot is ~635 mm (25″) in thickness. After scalping off ~12.7 mm (0.5″) from each rolling surface, the ingot is homogenized at ~600 °C for several hours, hot rolled to the re-roll gauge of 1.8–2.6 mm with a coiling temperature of ~350 °C, cooled down to room temperature, and cold rolled to the final gauge of ~0.255 mm (0.01″).

Alloy AA3104-H19 is formed into cans in several discrete stages, which are schematically illustrated in Fig. 1. The cupping operation is performed on one machine and the cups are then transferred to the body maker for redrawing, ironing and bottom doming. The metal must have acceptable earing and sufficient formability to go through the drawing and ironing processes. For cup drawing it is critical to achieve a balanced {001}⟨100⟩ cube texture and β-fibre texture (Bs {011}⟨211⟩, S {123}⟨634⟩ and Cu {112}⟨111⟩) in AA3104-H19. In practice, the balanced texture is obtained by the maximization of the cube texture in re-roll gauge and the control of subsequent cold rolling reduction. Fully recrystallized AA3104 re-roll typically gives a 4-eared cup with ears at 0, 90, 180 and 270° to the rolling direction. The other extreme in earing pattern is for highly cold worked materials which have four ears at 45, 135, 225, and 315. Final gauge AA3104-H19 alloy can have intermediate earing patterns which are a combination of these patterns to give either 4 eared, 6 eared cups or even 8 eared cups.

To predict earing in cup deep drawing, the main approach is to introduce texture related sheet anisotropy into the finite element method in sheet metal forming. The sheet anisotropy can be incorporated either through an anisotropic yield surface function (Hill, 1948; Barlat et al., 1991, 1997a, 1997b; Savoie et al., 1996; Tuğcu and Neale, 1999; Tuğcu et al., 2002; Barlat et al., 2003, 2005; Cazacu and Barlat, 2004; Wu et al., 2005) or through the incorporation of crystallographic texture in a crystal plasticity model (Nakamachi et al., 2001; Becker et al., 1993; Zhao et al., 2004; Miehe and Schotte, 2004; Raabe and Roters, 2004; Raabe et al., 2005; Chen et al., 2007; Yoon et al., 2010). The implementation of anisotropic yield functions into the finite element model to predict the cup earing was done by Gotoh and Ishise (1978) and Yang and Kim (1986) for a mild steel and Yoon et al. (2006) for aluminum. Yoon et al. modified the Barlet 2004 yield function and was able to predict cups with six or eight ears in the deep drawing of 2xxx aluminum alloy. All these yield functions require extensive experimental data, such as the yield stress and r-value directionalities to calibrate the yield function coefficients. The other disadvantage of the yield function approach, as discussed by Becker et al. (1993), is that

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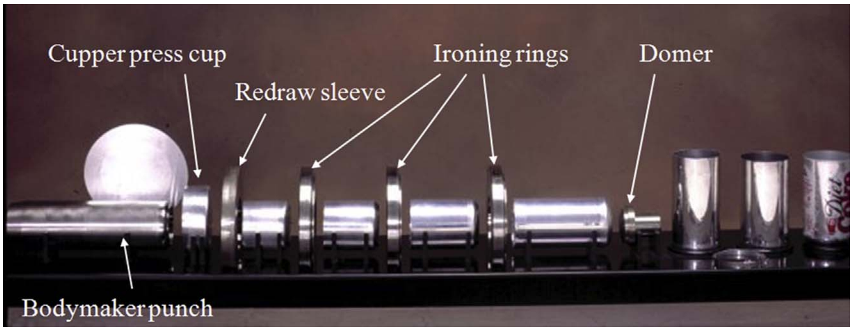

Fig. 1. Can making progression.

sheet texture evolution during the metal forming is not taken into account. The crystallographic texture-based crystal plasticity model directly incorporates crystallographic slip kinematics into finite element models by using the initial grain orientation from SEM EBSD or X-ray diffraction information. Recent investigations of earing through crystal plasticity modeling can be found in Zhao et al. (2004), Miehe and Schotte (2004), Raabe et al. (2005) and Chen et al. (2007). Zhao et al. (2004) studied the texture components in an aluminum alloy and found that minimum earing of cup drawn aluminium was obtained for a combination of the S and the cube texture components with 15 spherical scatter width. Raabe et al. (2005) conducted the similar study on steel. Their study reveals that 8, 6, or 4 ears can evolve during cup drawing depending on the starting texture and an increasing number of ears reduces the absolute ear height. It is worth noting that these studies of initial texture on subsequent cup earing are based on the several common texture components and their combinations. The real texture measurement from a commercial alloy sheet may exhibit a different texture profile, not only in terms of the volume fraction of each component, but also in its spatial distribution in the sheet after a high level of cold reduction.

In this paper, the can body alloy AA3104-H19 is investigated through both experimental work and a finite element-based crystal plasticity modeling to study the effect of the initial texture on cup earing. The FE model utilizes the grain orientations obtained from X-ray diffraction. The earing profiles of single crystal and polycrystal of AA3104 sheet will be studied. The potential influence of the initial texture and its spatial distribution on the earing type will be analyzed.

2. Experiments and experimental results

The experimental material was a 0.255 mm gauge AA3104-H19 commercial CBS (Can Body Stock), with a nominal composition of Al-0.8Mn-0.8Mg-0.5Fe-0.3Si. Coupon-sized specimens, 20 mm in the rolling direction (RD) and 14 mm in the transverse direction (TD), were prepared by electro-polishing to remove ~4 μm from the sheet surface in a solution comprising 2% butylcellosolve, 8% $HClO_4$, 30% alcohol and 60% water with current density of 1.5 A/cm^2 for 30 s at −10 °C.

The global texture was determined by the X-ray diffraction technique in a high intensity Rigaku X-ray machine with a radiation source of RU-200B rotating anode and Cr target. The X-ray beam has a length of 4 mm and a width of 1 mm determined normal to the specimen, and the specimen holder oscillates in a range of 8 mm in the direction of beam width. The region exposed to the X-ray is a circular area with a diameter of 9.85 mm, while the penetration depth of the X-ray is about 10 to 60μ m depending on the beam angle. The (111), (200), (220) and (311) pole figures were measured, and the orientation distribution functions (ODFs) were calculated using MTM-FHM software (Van Houtte, 2000). A Gaussian spread of 11° was used in the calculation of the volume fractions of different texture components.

The spatial distributions of texture components was investigated by the electron back scatter diffraction (EBSD) technique in a Philips XL30S field emission gun (FEG) scanning electron microscope (SEM) equipped with a Nordlys II detector. To maximize the indexing rate by removing some of the dislocations without triggering recrystallization, the electro-polished specimen was heat treated in an air furnace by an isochronal recovery annealing at 200 °C for one hour, 225 °C for one hour and 250 °C for another hour. Afterwards, the specimen was further electro-polished to remove another ~4 μm from the surface. The EBSD measurements were carried out at 25 kV and with 14 mm working distance. During automatic indexing, the band center of 4–6 Kikuchi bands were detected with static background correction, the Hough space resolution was set at 65 and a maximum mismatch angle of 1.3° was allowed. For each mapping a grid consisting of 1200 by 800 was scanned with a step size of 0.5 μm.

The (111) and (200) X-ray pole figures calculated based on ODF are shown in Fig. 2. The texture is typical for f.c.c. plane strain

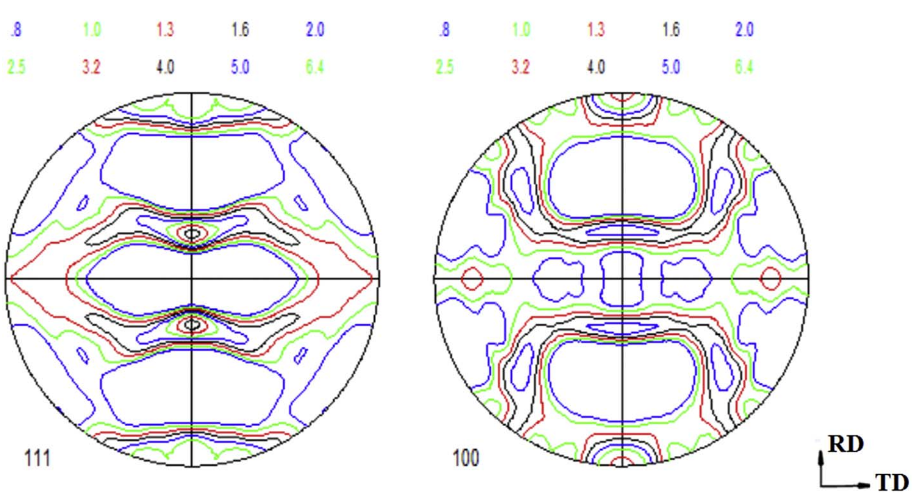

Fig. 2. The (111) and (200) X-ray pole figures of alloy AA3104-H19 used in the present work.