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Deformation texture evolution of pure aluminum sheet under electromagnetic bulging

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ABSTRACT

The deformation texture and microstructure evolution in pure aluminum sheet after electromagnetic bulging was investigated in detail by using electron backscatter diffraction (EBSD) and transmission electron microscope (TEM) techniques. It was found that the textural and microstructural developments were correlated with the complex strain path and the high strain rate. Stress–strain states from approximate uniaxial tension, non-equibiaxial tension to equibiaxial tension were experienced in the formed conical-shape workpiece along with the increasing strain ratio (i.e., the ratio between minor strain and major strain, representing the strain path of the formed workpiece). The grain orientation and distribution of boundary misorientation were found to be a function of the strain ratio, especially for the texture evolution in volume fraction of $\langle 110\rangle$ fiber. A specific orientation with high Taylor factor, Rotated Goss $\langle 110\rangle$, was observed and analyzed in terms of the contribution of preferable stress–strain state from the complex strain path and the assistance of high strain rate, which could increase the cross-slip activity, and eventually facilitate the texture development and induce more uniform microstructure.

1. Introduction

Electromagnetic forming (EMF) has received an increasing attention in recent years for the superiority of contact-free forming, low springback, high repeatability and enhanced forming limit [1–7]. The principle of EMF is to use electromagnetic force (i.e., Lorentz force) generated by pulsed magnetic field to shape metal workpiece without mechanical contact and working medium. This technique has already been used in materials processing and manufacturing, such as deep drawing, joining, coining, stamping and cutting [5].

EMF is a high velocity deformation process with strain rate ranging from $10^3\ s^{-1}$ to $10^4\ s^{-1}$ [5,8–10]. The high strain rate deformation can give rise to different deformation behaviors and unique microstructures and textures with respect to the conventional quasi-static or low strain rate deformation, thus affecting significantly the performance of the formed components. It was reported that high strain rate could lead to more uniform dislocation distribution and small dislocation-cell size as well as large misorientation [8–11]. In addition, twins were also expected to be formed in the metals with middle and even high stacking fault energy under high strain rate, as the thermally activated dislocation slip can be suppressed at high strain rate [12]. However, little work has been done on the study of microstructure, especially texture evolution of materials under electromagnetic forming.

With regard to common high strain rate deformation, for instance, shock deformation, there were hardly noticeable changes for texture in commercial pure aluminum [13], except for the $\langle 110\rangle$ texture and small changes in crystallographic orientation within grains. Similar behavior was also found in copper under high strain rate deformation [14]. The texture induced by uniaxial tension and compression was usually weak because of the increasing number of active slip systems resulting from the increased slip sensitivity under high strain rate [15]. However, Bhattacharyya et al. [16,17] reported that texture formation was closely related to lattice structure. For instance, inconspicuous change in texture was observed in BCC Fe after deformation at strain rate of $10^3\ s^{-1}$, but strong texture in FCC Cu was formed under the same deformation condition, due to that FCC Cu possesses a higher strain-hardening exponent (n). High n is more likely to increase misorientation resulting from dislocation accumulation, and consequently promotes grain rotation. More recently, after systemic investigation of texture evolution as a function of strain rate from $10^{-4}\ s^{-1}$ to $10^3\ s^{-1}$, Gurao et al. [18] pointed out that texture in FCC materials under high strain rate was dominant by the strain-hardening exponent, whereas little role for stacking fault energy (SFE).

EMF is usually experienced with high strain rate as what happened on shock deformation. The reduction of initial texture and increasing orientation near P $\{110\}\langle 111\rangle$ and Brass $\{110\}\langle 112\rangle$ was observed in the electromagnetic bulging of aluminum sheet

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[9]. The weak texture was regarded as the result of the formation of discontinued sub-grains at high strain rate. This was in good agreement with the further analysis by Risch et al. [19], who proposed that the aluminum alloy (AA5183) specimen under EMF could have three preferred orientations, i.e., [1 1 1], [1 1 0] and [1 0 0], which all were considered to contribute to the dislocation motion and texture evolution. However, Risch offered no further details in explanation of texture evolution considering the complex strain path under electromagnetic bulging.

The deformation texture as a function of strain path was previously studied under normal deformation. One typical strain path related texture component is Rotated Goss, i.e., $\{110\}\langle 110\rangle$, which was rarely reported in usual tension deformation or traditional rolling, but was frequently observed in the recrystallization of Interstitial-Free (IF) steel by hot rolling [20]. Rotated Goss orientation is particular due to its high Taylor factor of 4.24 [21] or 4.90 [22]. Since Taylor factor is proportional to the amount of slip systems being necessary for a certain strain. The grains with Rotated Goss orientation are considered to be hardly deformed compared to those with other orientations. In addition, Rotated Goss texture was also observed in the cross rolling [23,24] and channel die compression [25,26]. Under cross rolling (rolling along the original transverse direction), the Goss component could change into the Rotated Goss $\{110\}\langle 110\rangle$ component, due to a 90° rotation around the normal direction. For channel die compression, a method similar to cross rolling was employed to study the plastic flow of $(110)[1\bar{1}0]$ orientated single crystalline copper. As compared to the strain-path induced Rotated Goss, a dominant texture component $\langle 110\rangle$//ND (ND referring to normal direction) fiber was observed in other deformation modes, for instance, plane strain tension of aluminum alloy [27,28], plane compression of copper [26], uniaxial compression of Ni alloy [29] and equibiaxial stretching deformation [30–32]. What is more, in the equibiaxial stretching of aluminum, copper and Cu30%Zn alloy [33], Kohara observed that the texture of $\langle 110\rangle$//ND fiber was apt to be the main texture component in these metal sheets with different initial textures. However, little work has been done on the texture evolution with the influence of strain path under high strain rate deformation.

Concerning EMF, most of the research work in the past years mainly focused on the development of equipment systems [19,34,35] and finite element simulation of processing [36–38]. There is lack of work on texture evolution under EMF. In the present work, the texture evolution of the aluminum sheet with initial Rotated Cube orientation under EMF was studied. The effects of strain path and high strain rate were both taken into consideration to understand the change of the microstructural morphology and crystallographic orientation in Al sheet under EMF. For simplicity, a strain ratio between the minor strain and major strain was regarded as the parameter reflecting the change of the strain path of the formed workpiece [30,39]. A detail investigation of two texture components, Goss and Rotated Goss, was carried out to examine the effect of strain path and high strain rate on the texture evolution.

2. Experimental procedure

2.1. Electromagnetic forming

The commercial pure Al (1050A) sheet with thickness of 1 mm and purity of 99.5 wt% was used in this study. Disk samples with a diameter of 180 mm for EMF experiments were prepared by wire-cutting from the sheet. The electromagnetic bulge method (free bulge without mold) was applied for electromagnetic deformation of the Al disk. In order to adequately eliminate the defects existed in the as-received rolled sheet and consequently allow an profound study of the microstructure evolution [8,9,19], the Al sheet obtained was annealed in a furnace at 500 °C for 5 h, propelling the formation of approximate equiaxial grains with average grain size of about 130 μm. Then, as illustrated in Fig. 1a, the annealed sheet was deformed by the sudden pulse of the electromagnetic force that was generated by the inductive eddy current effect [5], and yielded a conical shape workpiece. The applied charging voltage and capacitance for EMF were 14 kV and 80 μF, respectively.

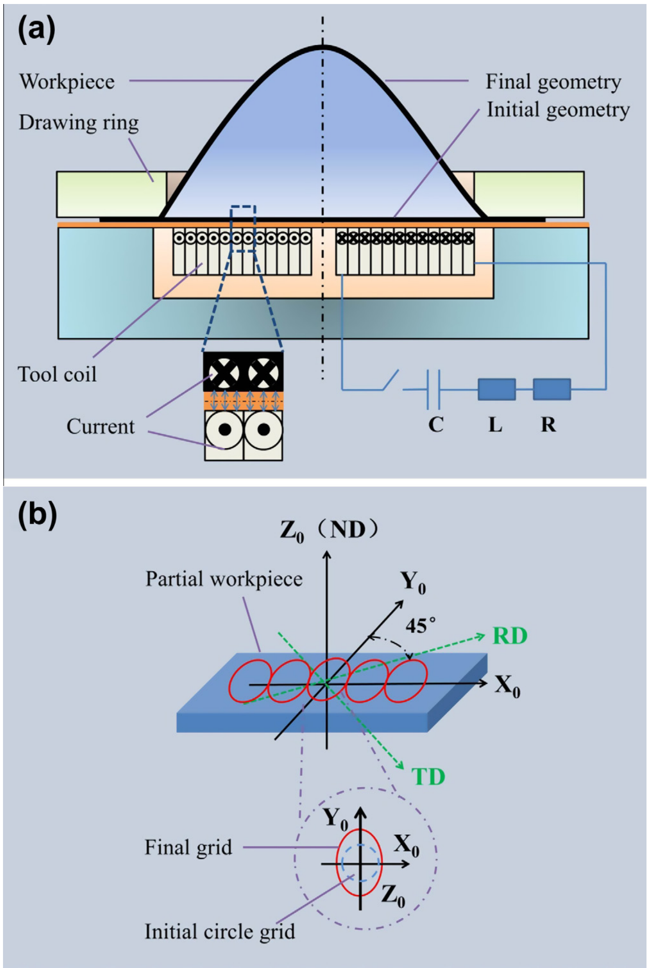

Fig. 1. Schematic diagram of (a) electromagnetic sheet metal forming, and (b) the original rolling coordinate system (RD-TD-ND with dash line in green) and tensile coordinate system (X_0–Y_0–Z_0 with real line in black): RD for rolling direction, TD for transverse direction and ND (Z_0) for normal direction, Y_0 for direction of major strain and X_0 for direction of minor strain. Strain change of the circle grid under the normal direction is also enlarged and displayed in the figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2.2. Stain analysis

In order to measure the strains along different directions, circle grids of 2.5 mm diameter were gridded by screen printing on the aluminum disk prior to electromagnetic bulging. Strain analysis was carried out with commercial software (ASAME Lite Version 4.1) by measuring the change of the circles. Since the deformation was not uniform, the grid circles were deformed into ellipses after electromagnetic bulging. Here, we mainly concerned the major strain (ε_{Maj}) and minor strain (ε_{Min}), where major strain and minor strain were defined as the true strain along the Y_0 direction and X_0 direction, respectively, as schematically illustrated in Fig. 1b. The strain ratio between minor strain and major strain, i.e.,

$$\eta = \frac{\varepsilon_{Min}}{\varepsilon_{Maj}}$$

was used to describe the change of strain path. As shown in Fig. 1b, the texture coordinate system of EMF is defined according to the traditional rolling coordinate system (i.e., RD referring to the rolling direction, TD to the transverse direction and ND to the normal direction, respectively) which is changed with an anticlockwise rotation of 45° around Z0 (ND). Thus, in the texture coordinate system, there is a new definition with Y0 paralleled to tensile axis of major strain, X0 paralleled to tensile axis of minor strain and Z0 coincided with the normal direction of the sheet plane.