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Influence of cold rolling reduction on the deformation behaviour and crystallographic orientation development

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ABSTRACT

In the present paper, a systematic study has been conducted aiming to attain an insight into the influence of rolling reduction on the deformation behaviour and crystallographic orientation development during cold rolling. Simulations were successfully carried out using a crystal plasticity finite element method (CPFEM) model with the highest reduction of 80%. Aluminium single crystals with initial ideal Cube orientation ($\{001\}\langle100\rangle$) were selected in order to avoid the influence of grain boundaries. The results revealed the development of deformation matrix bands through the billet thickness, parallel to the rolling direction, which have been observed in the experiment in the literature. The sign of rotation angles in the neighbouring matrix bands are opposite with each other, even at the reduction of 80%. The corresponding {1 1 1} pole figures offered direct evidence of the spread of crystallographic orientation around the transverse direction. It is clear from the current study that the rolling reduction significantly influences the deformation heterogeneity which leads to the inhomogeneous texture evolution, non-uniform distributions of macroscopic stress and strain in the cold rolled samples. The slip system activity has been examined in detail and the predicted results are consistent with the early reported experiments.

1. Introduction

It has been established for a long time that the formability of sheet metal is significantly influenced by its initial and plastic deformation induced anisotropies, which can be characterised by the crystallographic texture, and therefore texture should be introduced into finite element analysis to predict its formability with a high degree of accuracy [1]. As the development of computer skills, modelling tools have become an attractive means of studying the texture evolution during plastic deformation. By far, the crystal plasticity finite element method (CPFEM) model has been recognized as one of the most effective models for simulating plastic deformation of crystalline materials and predicting the deformed textures [2,3], whereas the classic full constrained (FC) Taylor model becomes inaccurate at large strains which assumes the strain in a grain is the same with the imposed macroscopic strain [4]. Crystal plasticity models have enjoyed major successes in predicting the texture evolution during a broad range of deformation processing operations, including rolling, plane strain compression, equal channel angular pressing, and tension [5–9]. The main advantage of CPFEM lies in their ability to solve crystal mechanical problems at both microscopic and macroscopic scales [10].

Up to now, the deformation behaviour and texture evolution during rolling have been studied extensively by X-ray diffraction (XRD), the electron back scattering pattern (EBSP) technique in the scanning electron microscope (SEM), and the transmission electron microscopy (TEM) [11–22]. The texture of aluminium alloy sheets produced by cold rolling is generally characterised by components that belong to the β-fibre texture, which changes to Cube texture after annealing [23]. It was found that the texture might be inhomogeneous through the thickness of rolled plates due to the rolling gap and frictional conditions during rolling [24,25] and the non-uniformity of the recrystallisation that occurred during heat treatment [23,26]. During cold rolling, the macroscopic deformation is distributed heterogeneously among the individual grains and the behaviour of each grain is determined by its crystallographic orientation and the activated slip systems. Therefore, in order to gain a better understanding of the development of deformation textures in polycrystalline aluminium, a great deal of effort has been made to investigate the deformation of single crystals without considering the influence of the grain boundaries. Most of these studies concentrated on typical stable rolling texture components such as S orientation ($\{123\}\langle634\rangle$) in [27–29], Brass orientation ($\{110\}\langle112\rangle$) in [13], Copper orientation

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({112}⟨111⟩) in [13,16], and Goss orientation ({110}⟨001⟩) in [14–16]. In addition, the meta-stable Cube orientation ({001}⟨100⟩) has also been investigated [5,13–20]. Recently, Wert investigated the dislocation boundary formation deformed by cold rolling using the EBSP and TEM methods [16,17] and explained the salient aspects of crystal rotation patterns by the enforced redundant strain pattern [15]. Furthermore, Liu and co-workers examined the macroscopic and microscopic sub-division of a single crystal in [18] and then proposed a direct relationship between the location dependent shear and the macroscopic sub-division of the crystal in [14]. The experimental results in [18] have been confirmed by a recent theoretical analysis by Si and co-workers in [5], where they also revealed the influence of the friction between the billet and the rolls on the texture evolution of aluminium single crystals. It has been found that the friction only affects the region near the billet surface.

However, the majority of studies on the aluminium single crystals initially oriented with Cube orientation have been subjected to the rolling reductions in the range of 10–50%. To the best of our knowledge, the texture simulations based on the CPFEM model with reductions >50% have not been reported yet for Cube oriented aluminium single crystals. Therefore, this study is specifically designed and the influence of rolling reductions up to 80% on the deformation heterogeneity, texture evolution and the slip activity will be examined.

2. Finite element analysis

2.1. Material modelling

The crystalline material under load undergoes crystallographic slip due to dislocation motion on the active slip systems and elastic deformation stretching and rotating of the crystal lattice. In order to avoid the slip system and stress response ambiguity problem, the crystal plasticity model adopted in this study is based on the rate-sensitivity of slip in the {111}⟨110⟩ slip systems of a face-centered cubic (FCC) crystal [5]. All geometrically possible slip systems are activated with this model, and it is expressed by a power law relation between the shear strain rate $\dot{\gamma}^{\alpha}$ and the resolved shear stress τ^{α}:

$$\dot{\gamma}^{\alpha} = \dot{\gamma}_0^{\alpha}\ \mathrm{sgn}\ (\tau^{(\alpha)})\left|\frac{\tau^{(\alpha)}}{\tau_c^{(\alpha)}}\right|^n \quad (1)$$

In Eq. (1), n represents the rate sensitive exponent and α is the slip system index. $\dot{\gamma}_0^{\alpha}$ is the reference value of the shear strain rate, and is taken to be a constant for all slip systems. The hardening law introduced by Bassani and Wu [30] has been adopted here to describe the flow and strain hardening that occurs on crystallographic slip systems. The material parameters for all simulations reported in this paper are given in detail in [5]. The elastic moduli

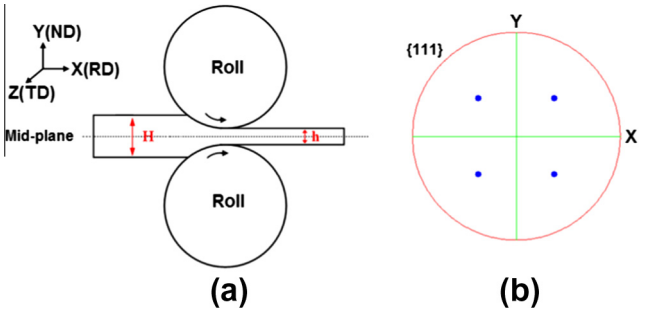

Fig. 1. (a) Schematic illustration of rolling process and the coordinate system considered in the present study. (b) {111} Pole figure of initial crystallographic orientation.

C_{11} = 112000 MPa, C_{12} = 66,000 MPa and C_{44} = 28,000 MPa. The aluminium single crystals are initially oriented with Cube orientation ({001}⟨100⟩). The {111} pole figure has been plotted in Fig. 1b. The 12 slip systems of face-centered cubic (FCC) material considered in this study are listed in Table 1, and the corresponding simulation data has been collected for investigating how the texture evolves after rolling.

2.2. Simulation details

The finite element analysis in the present study was carried out by applying the FE-code Abaqus/Standard ver.6.9-1. Fig. 1a shows a schematic illustration of the rolling and the coordinate system, i.e. X is the rolling direction (RD), Y is the normal direction (ND), and Z is the transverse direction (TD). A two-dimensional simulation of the rolling process has been conducted by assuming plane strain condition in order to save computing time. Because of symmetry, only one half of the billet (half thickness = $H/2$) has been considered in the FE analysis. During the simulations, the roll is considered to be an analytically rigid body and the billet is considered to be a deformable body meshed into 7293 four-node plane strain elements. The roll is 125 mm in diameter and its speed is 196 mm s^{-1}. The friction between the roll and the billet is incorporated through the Coulomb's friction law with the coefficient μ = 0.1. Three rolling reductions of 50% (case I), 60% (case II), and 80% (case III) have been simulated, respectively. The initial rolling conditions have been summarised in Table 2. It should be noted that for both the experiments and simulations at high reductions, the head of each billet needs to be cut into wedge in order to bite in before starting cold rolling.

3. Results and discussion

In Fig. 2a–c, a comparison of the distribution of von Mises stress during cold rolling between reductions of 50%, 60%, and 80% has been done. These variations of stress reveal the degree of inhomogeneous deformation along the billet axis (or rolling direction) and its thickness (or normal direction). As can be seen, a higher reduction leads to a larger stress and a more inhomogeneous distribution. The meshes in the centre of the billet are not as distorted as

Table 1
The slip systems considered in the present study.

Slip system	Slip plane	Slip direction
a1	111	0−11
a2	111	10−1
a3	111	−110
b1	−111	101
b2	−111	110
b3	−111	0−11
c1	1−11	011
c2	1−11	110
c3	1−11	10−1
d1	11−1	011
d2	11−1	101
d3	11−1	−110

Table 2
The initial rolling conditions for FE analysis.

Case	Length (mm)	$H/2$ (mm)	Reduction (%)	Roll diameter (mm)	Roll speed (mm s^{-1})	μ
I	30	1.5	50	125	196	0.1
II	30	1.5	60	125	196	0.1
III	30	1.5	80	125	196	0.1