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Evolution of recrystallization textures in particle containing Al alloys after various rolling reductions: Experimental study and modeling

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ABSTRACT

The presence of large elastic constituent particles in aluminum alloys triggers strain heterogeneities in rolled materials. Finite element calculations demonstrate that the strain field in the vicinity of non-deformable particles strongly deviates from the macroscopic one, which induces a specific texture in the particle affected deformation zone during recrystallization. Results of the current study reveal that after various degrees of rolling reduction the corresponding recrystallization textures show significant qualitative and quantitative differences with respect to each other. The evolution of recrystallization textures is explained by a model which combines both orientation selection during nucleation and micro-growth selection. The current texture simulation provides very satisfactory results and suggests that the evolution of the $\{100\}\langle 130\rangle$ and $\{011\}\langle 233\rangle$ components in recrystallized materials is related to the well-known particle stimulated nucleation mechanism.

1. Introduction

Evolution of the recrystallization texture in a polycrystalline aggregate is strongly dependent on the deformation history of the material. Polycrystalline materials with face centered crystal (FCC) structure such as Al alloys reveal a specific rolling texture, which exhibits the well-known β-fiber (Hirsch and Lücke, 1988; Humphreys and Hatherly, 2004). A recent analytical description of rolling textures in FCC metals (Sidor and Kestens, 2013) reveals that orientations of the skeleton line connecting the Copper ($\{112\}\langle 111\rangle$) and Brass ($\{011\}\langle 211\rangle$) components are unified in the β-fiber via the following expression:

$$\{h,\quad 1,\quad h+1\}\left\langle \frac{h(h+1)}{3/4-h},\quad \frac{2h(h+1)}{1/2-h},\quad \frac{h^2}{h-3/4}+\frac{2h}{h-1/2}\right\rangle \tag{1}$$

The presence of non-deformable particles in commercially produced aluminum alloys triggers additional strain hardening due to the gradients of deformation proportional to the particle spacing (Ashby, 1966, 1970). The strain heterogeneity (Ashby, 1970) during deformation in the vicinity of large hard inclusions (larger than 1 μm) gives rise to the creation of a particle affected deformation zone (PADZ). In the PADZ, the lattice is substantially misoriented with respect to the particle-free matrix. The magnitude of the rotation is related to the shear strain, the particle diameter and the radius of the

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rotated zone (Humphreys, 1977; Xu et al., 2007) whereas the misorientation in the PADZ follows declining trend with increasing distance from the particle (Humphreys, 1979). This implies that the deformation texture in the PADZ deviates significantly from the texture of the particle-free matrix, which is usually aligned along the β-fiber. Apart from the particle size and strain magnitude, the local lattice rotation depends on the macroscopic strain mode and the particle shape. Humphreys (Humphreys, 1979) has reported lattice rotation about $\langle 1\,1\,1\rangle$, $\langle 1\,0\,1\rangle$ and $\langle 1\,2\,1\rangle$ axes in tension whereas Engler (1997a) has observed matrix rotation around $\langle 1\,2\,1\rangle$ axes and the transverse direction (TD) in cold rolled particle containing Al alloys. Significant local distortions of the deformed microstructure in the PADZ are reported by Liu et al. (2009). It is claimed that a symmetric pattern of TD-rotations of alternating sign are found in the PADZ while the largest lattice rotations occur at the tip of elongated particles. Extensive TD rotation is also observed in particle containing ferritic steel (Pinto De Siqueira et al., 2013) whereas the results of an investigation with electron back scattering diffraction (EBSD) suggest that the crystal lattice rotation around TD is independent of the initial crystal orientation which is additionally confirmed by the work of Humphreys and Ardakani (1994).

The fact that the misorientation changes inside the PADZ implies that the strain is also distributed heterogeneously. Various numerical techniques such as finite element modeling (FEM) (Ohashi, 2004; Schäfer et al., 2009), crystal plasticity FEM (CPFEM) (Dunne et al., 2012) and gradient plasticity (Humphreys and Bate, 2003) have been employed to address the problem of strain distribution in the PADZ. Results of both FEM (Schäfer et al., 2009) and CPFEM (Dunne et al., 2012) show that heterogeneous strain distribution around the elastic particle involves a vast spectrum of strain modes. The local strain mode and the magnitude of the localized strain depend on the particle shape and the distance from the particle. Independently from the distribution, shape and size of large particles ($d > 1\ \mu$m) the strains are always higher in the PADZ compared to the particle-free domains as it is reported by Wilkinson and Dingley (1992), Barlow and Liu (1998), Humphreys and Bate (2003), Konrad et al. (2006), Schäfer et al. (2009), and Dunne et al. (2012). The higher accumulated strains result in locally higher driving force for recrystallization (RX). During annealing, the first recrystallized nuclei appear in the vicinity of the large particles and this phenomenon refers to the well-known recrystallization mechanism of particle stimulated nucleation (PSN), whereas the particle-free matrix, which exhibits the conventional rolling texture (β-fiber), commonly transforms to a texture that is dominated by the Cube ($\{1\,0\,0\}\langle 0\,0\,1\rangle$) and weak Goss ($\{1\,1\,0\}\langle 0\,0\,1\rangle$) components (Humphreys and Hatherly, 2004; Engler and Hirsch, 2002; Doherty et al., 1993; Ridha and Hutchinson, 1982). Both strain heterogeneities and local lattice rotations in the PADZ cause a specific texture development (Engler and Hirsch, 2002; Daaland and Nes, 1996; Lücke and Engler, 1990; Juul Jensen et al., 1985).

The evolution of the deformation texture in single phase alloys was successfully modeled with various Taylor-type homogenization crystal plasticity (CP) models (Lebensohn and Tomé, 1993; Van Houtte et al., 2005; Engler et al., 2007, Sidor et al., 2008a, 2008b; Kanjarla et al., 2010; Rossiter et al., 2010; Wang et al., 2013). The recently developed crystal plasticity finite element approaches (Delannay et al., 2006; Jung et al., 2013) are computationally demanding and thus a new generation of CP formulations with enhanced homogenization schemes are based on fast Fourier transforms (Lebensohn, 2001; Lebensohn and Kanjarla, 2012) or spectral interpolation (Knezevic et al., 2008; Shaffer et al., 2010). These models enable analyzing the evolution of the deformation texture as well as estimating the dissipated plastic power in each crystal orientation during deformation. Additionally, the CP models offered a platform for a vast variety of RX models (Jonas and Toth, 1992; Bunge and Kohler, 1992; Vatne et al., 1996; Kestens and Jonas, 1996; Engler, 1997a, 1997b; Lebensohn et al., 1998; Crumbach et al., 2006; Sidor et al., 2011). Modeling RX texture evolution is far more complex compared to simulation of deformation textures since a particular local event in RX can give rise to significant long range effects that may drastically affect the overall texture evolution. A typical example is abnormal grain growth occurring when a specific nucleus consumes the surrounding deformed or recrystallized matrix due to particular local events such as variant selection or solute drag of neighboring boundaries. Giving the complexity of the processes involved in RX the goal of building a comprehensive, accurate and relevant model for industrial application has not yet been achieved. In this respect, the current contribution aims to clarify the effect of strain heterogeneities involved in severe rolling reductions of particle containing Al alloys on the development of recrystallization texture, based on results obtained from both finite element modeling and crystal plasticity calculations. The simulation of recrystallization textures is performed by a model which combines growth selection phenomena and orientation selection (OS) taking into account various strain modes in the PADZ.

2. Experimental and computational methods

The material used in the current study is a cast Al–2.8 Mg–0.21Mn–0.14Si aluminum alloy from the 5xxx series. The as-cast block was subjected to 5 different cold rolling reductions of 74.2%, 85.0%, 95.9%, 96.9% and 99.1% (denominated as sheet A, B, C, D and E, respectively), corresponding to a true strain of 1.35, 1.90, 3.21, 3.50 and 4.76, respectively. In the current case, the as-cast block was laboratory cold rolled without homogenization heat treatment with the aim to preserve a minimum level of fine precipitates and thus to reveal the effect of large non-deformable particles on the evolution of the recrystallization texture. The rolling was performed on well lubricated surfaces of both sheet and rolling cylinders (with diameter of 400 mm). With the aim to avoid strong strain heterogeneities, the contact length to mean thickness ratio (l/h) was kept above 1.0. The fist 40% deformation was performed with intermediate draughts (l/h varied from 1.2 to 1.7), whereas from 40% to 70% the material was rolled with l/h changing from 1.7 to 2.9. Rolling from 70% to a final thickness was carried out with l/h ratio raising from 3.0 to 25.8. This deformation schedule guarantees a homogenous strain distribution across