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A microstructure-based model for describing the material properties of Al–Zn alloys during high pressure torsion

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ABSTRACT

In this work, super saturated solid solution Al–30 wt%Zn alloy was subjected to high pressure torsion (HPT). The material properties and microstructural evolution were experimentally studied. Despite strong grain refinement during HPT, the process of softening is observed. Such a material behavior is captured by a proposed model (MBWG) that takes into consideration the effects of solid solution hardening, Orowan looping and evolution of the dislocation density. Namely, the softening process occurred during HPT is attributed to decomposition of super saturated solid solution and evolution of the dislocation mean free path with plastic strain. Our simulation shows that the proposed model describes well the softening and saturation processes, and the decomposition of solid solution plays a significant role during the HPT process.

1. Introduction

Several techniques of severe plastic deformation (SPD) such as equal channel extrusion, asymmetric rolling and high pressure torsion (HPT) have been developed to improve the mechanical properties of metals (Segal, 1995; Valiev et al., 2000; Valiev and Langdon, 2006; Khan and Meredith, 2010; Meredith and Khan, 2012; Seipp et al., 2012). Among these techniques, HPT is especially effective to introduce extremely large shear strain due to the occurrence of strong grain refinement (Valiev and Alexandrov, 1999; Zhilyaev et al., 2003; Zhilyaev and Langdon, 2008). The HPT process has been the subject of many investigations as a new method of processing for nanostructured materials due to its ability to develop homogeneous nanostructures with high-angle grain boundaries (Valiev, 2003; An et al., 2010). The effect of HPT on the mechanical behavior and alterations of microstructural features have been investigated extensively for a wide range of pure and alloyed metals (Islamgaliev et al., 1997; Mishra et al., 1998; Zhilyaev et al., 2001, 2003, 2005; Sakai et al., 2005; Lugo et al., 2008; Edalati et al., 2008, 2009, 2011; Todaka et al., 2008; Ito and Horita, 2009; Edalati and Horita, 2011; Ni et al., 2011; Srinivasarao et al., 2013). The previous investigations have shown that the application of HPT to aluminum-based alloys leads to both a small grain size and a high level of microhardness (Wang et al., 1996; Stolyarov et al., 1997; Islamgaliev et al., 2001; Gubicza et al., 2007; Loucif et al., 2010; Valiev et al., 2010; Zhang et al., 2010; Ghosh et al., 2012; Tugcu et al., 2012; Sabirov et al., 2013). In the work of Islamgaliev et al. (2001), nanostructured Al–Zn–Cu–Mg–Zr alloys after HPT demonstrated tensile strengths (up to 800 MPa). Harai et al. (2009) and Xu et al. (2007) have investigated the evolution of the mechanical behavior for pure aluminum during the HPT process. The results show that the hardness of pure Al initially increases with increasing strain,

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and then, after reaching a maximum value, decreases to a constant level. Xu et al. (2007) attributed an unusual softening phenomenon at large strain to easy cross-slip and dynamic recovery due to a large stacking fault energy (SFE) of Al.

Despite the large quantity of studies that have been carried out on HPT, most of them are only dedicated to microstructural evolution and mechanical characterization (Zhilyaev and Langdon, 2008). However, in the past few years, many researchers have attempted to develop various dislocation models to describe microstructural evolutions under large imposed strains (Langlois and Berveiller, 2003; Khan et al., 2006; Khan and Farrokh, 2006; Beyerlein and Tomé, 2007; Mayama et al., 2007; Farrokh and Khan, 2009; Groh et al., 2009; Starink et al., 2009; Austin and McDowell, 2011; Li and Soh, 2012; Ostapovets et al., 2012; Oppedal et al., 2012; Aoyagi et al., 2013; Bertin et al., 2013; Hansen et al., 2013; Kitayama et al., 2013; Lee et al., 2013; Wen et al., 2013). In the physically-based model developed by Starink et al. (2013), it was possible to predict the increment of hardness and grain refinement of pure metals during the HPT process. This model takes into account dislocation and grain boundary strengthening by incorporating the volume-averaged thermally activated dislocation annihilation and the grain boundary formation.

The most common models of grain refinement due to large strain, particularly under HPT, are usually based on the notion that the dislocation cell structure, which forms in the early stage of plastic deformation, gradually transforms to a fine grain structure. This type of models are based on the approach of Kocks and Mecking (2003), which describes the deformation behavior of metals and alloys in terms of a single internal variable, namely, the total dislocation density. Estrin et al. (1998) proposed a constitutive model that describes the hardening behavior of cell-forming crystalline materials at large strains. This model considers the evolution of the dislocation densities in the cell walls and the cell interiors. Zhang et al. (2011) developed a microstructural model that is based on the evolution of geometrically necessary dislocations and statistically stored dislocations that incorporate grain refinement. A key element of this model is the assumption that, at the very high strains developed in HPT, the dislocation density reaches a saturation value.

In a previous work (Mazilkin et al., 2012), it was shown that HPT of Al–30 wt%Zn alloy induces a strong grain refinement. Surprisingly, the corresponding material behavior consists in a continuous strain softening. Strain softening is usually found during hot working as a result of dynamic recovery and dynamic recrystallization. However, at room temperature, occurrences of softening were recently reported in metals subjected to SPD and were attributed to the occurrence of concomitant phenomena such as dynamic recovery, dynamic recrystallization, high-angle grain boundary development and supersaturated solid solution decomposition (Mazilkin et al., 2012). However, the existing models have not been able to connect the flow stress with the observed microstructure evolution.

In a previous work, Borodachenkova et al. (2013) made an attempt to develop a new microstructure-based model to explain the softening during HPT. The model consisted in two main components: (i) in the first stage of plastic deformation, the material behavior is dictated by the gradual increase of the dislocation mean free path resulting from precipitation, and diffusion of Zn atoms towards the grain boundary; (ii) in the second stage, further grain refinement to nanoscale size promotes a dramatic increase in strain rate due to the diffusion-driven grain-boundary sliding according to the theory of Raj and Ashby (1971). However, with this model, the contribution of different strengthening mechanisms was not evaluated.

The purpose of this paper is to explain with a microstructure-based model the evolution of the critical resolved shear stress with the accumulated shear strain during the HPT process. This model takes into account the contribution of different strengthening mechanisms such as dislocation multiplication, Orowan and solid solution hardening. The model is based on the understanding of microstructural evolution and the interaction of dislocations with the microstructure essential features.

2. Experimental details

Al–30 wt%Zn alloy was prepared by induction melting in vacuum from high purity elements (5N Al and 5N5 Zn). After melting, the alloy was poured in vacuum into a water-cooled copper crucible with an internal diameter of 10 mm. Samples of the alloy were cut by spark machining in the disks with a thickness of about 1 mm and diameter of 10 mm, and then

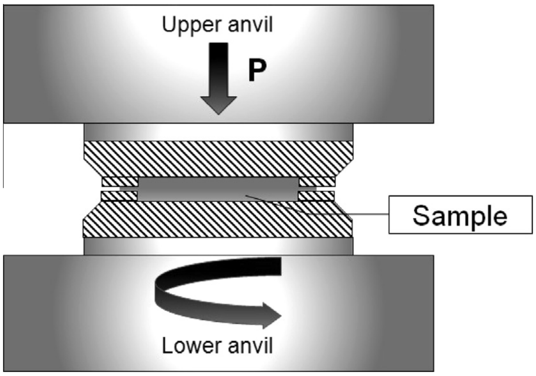

Fig. 1. Schematic illustration of quasi-constrained HPT setup.