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Mechanical responses and deformation mechanisms of an AZ31 Mg alloy sheet under dynamic and simple shear deformations

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ABSTRACT

The mechanical responses and deformation mechanisms of AZ31 Mg alloy sheets were studied under dynamic (tension and compression) and simple shear deformations along different in-plane loading directions. This paper is a continuation of the author's previous manuscript (Khan et al., 2011) on the quasi-static responses and texture evolution of AZ31 Mg alloy sheets. The strain-hardening rate ($d\sigma/d\varepsilon$) of specimens under in-plane dynamic compression at room temperature showed a strong strain-rate dependency when deformation entered the dynamic region. The electron back-scattered diffraction (EBSD) technique was used to conduct texture analysis on each specimen after simple shear deformation under a quasi-static load ($10^0\ s^{-1}$) at 150 °C and after dynamic compression under a strain rate of 1500 s^{-1} at RT and 150 °C. Loading direction during simple shear deformation did not significantly affect either the texture evolution or the twinning evolution. Deformation temperature during dynamic compression affected both the texture evolution and the twinning evolution only slightly, but it significantly affected the kernel average misorientation (KAM) distribution in deformed grains. A visco-plastic self-consistent (VPSC) polycrystal model was successfully used to simulate the mechanical responses and the evolution of the initial texture in an AZ31 Mg alloy sheet during simple shear deformation and dynamic compression.

1. Introduction

Magnesium (Mg) alloy has been used extensively in the automotive field due to its high strength-to-weight ratio (Mordike and Ebert, 2001). In addition, weight reduction has emerged as one of the most attractive options of automobiles for significant advances in both fuel efficiency and a resultant reduction in CO_2 emissions (Avedesian and Baker, 1999; Aghion and Bronfin, 2000; Luo et al., 2007). Characteristics such as low ductility and formability at room temperature (RT) and near RT limit the use of Mg alloys for widespread structural applications (Doege and Dröder, 2001; Yin et al., 2005; Agnew and Duygulu, 2005), due to the limited number of operative slip systems at and near RT (Kelly and Hosford, 1968; Agnew et al., 2001). However, at elevated temperatures, pyramidal $\langle c + a \rangle$ slip occurs at lower critical resolved shear stress (CRSS) and most Mg alloys, including AZ31, then become quite formable (Agnew et al., 2001; Agnew and Duygulu,

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2005). The deformation mechanisms of Mg and its alloys have been studied extensively under quasi-static loading (Jain and Agnew, 2007; Choi et al., 2007, 2008, 2009; Khan et al., 2011). It is generally accepted that, at temperature near RT, Mg alloys with a hexagonal close packed (HCP) structure can accommodate external deformation via the activation of four slip systems and two twinning systems: basal ⟨a⟩, prismatic ⟨a⟩, pyramidal ⟨a⟩, pyramidal ⟨c + a⟩, tensile twinning, compressive twinning and double twinning (Nave and Barnett, 2004; Jiang et al., 2006; Barnett, 2007a, 2007b; Jain and Agnew, 2007; Choi et al., 2011). Even though the CRSS value is the key factor in determining the significance of each mechanism, other parameters—the loading directions with respect to the c-axis of the HCP unit cell, the temperature and the strain rate—could change the relative activity of the deformation mechanisms. Under the quasi-static loading of Mg alloys, macroscopic responses such as flow curve and plastic strain ratio were significantly dependent on the external deformation path (Gehrmann et al., 2005; Yi et al., 2006; Lou et al., 2007; Jain and Agnew, 2007; Choi et al., 2007, 2008, 2009). If rolled Mg alloy sheets are subjected to in-plane compression, twinning alongside the basal ⟨a⟩ slip accommodates plastic deformation. In contrast, prismatic ⟨a⟩ slip which has a higher value of CRSS than basal ⟨a⟩ slip accommodates plastic deformation as a primary mode during in-plane tension (Wang et al., 2010; Agnew et al., 2001; Agnew and Duygulu, 2005). The testing temperature can also affect mechanical responses by changing the CRSS values. Chapius and Driver (2011) showed that CRSS for both basal ⟨a⟩ slip and tensile twinning was almost constant at the temperatures ranging from 25 to 450 °C, while the value of CRSS for other mechanisms dropped rapidly as the temperature increases. By assuming a temperature-insensitive CRSS for basal ⟨a⟩ slip, Jain and Agnew (2007) simulated the mechanical response of a rolled AZ31 Mg alloy sheet at a temperatures ranging from 22 to 250 °C. They shoed that varying temperatures might not change the yield strength as long as basal ⟨a⟩ slip controls the yielding.

The further developments of Mg alloys in the automotive, aerospace and defense industries will require more research on the mechanical responses and deformation mechanisms under dynamic loading and high-temperature conditions where the machine components undergo severe conditions such as crash testing. The most recent studies regarding mechanical responses and the related deformation mechanisms under dynamic loading and high-temperature conditions have focused on cubic structure materials such as aluminum alloys, OFHC copper, and high strength steels (Pandey et al., 2013; Khan et al., 2012; Baig et al., 2013). Few studies have focused on the mechanical responses and deformation mechanisms of Mg alloys under dynamic loading and high-temperature conditions (Ishikawa et al., 2005; Tucker et al., 2009; Ulacia et al., 2010; Dudamell et al., 2011). Tucker et al. (2009) have performed dynamic ($\sim$3800 s^{-1}) and quasi-static (10^{-3} s^{-1}) compression tests on rolled AZ31B-H24 Mg alloys and found a strong strain-rate dependency on the yield stress, strain-hardening and failure strain in the normal direction (ND), but almost none for in-plane directions. Ulacia et al. (2010) had similar observations for in-plane compression tests. However, during tension testing in both the rolling direction (RD) and the transverse direction (TD), there were significant variations in the flow stresses as the strain increased. In particular, only two strain-rate conditions (10^{-3} s^{-1} and 10^3 s^{-1}) were insufficient to capture the effect of strain rate on the mechanical responses of an AZ31 Mg alloy sheet. Moreover, only the microtexture evolution of the AZ31 Mg alloy sheet during dynamic tension was analyzed. Dudamell et al. (2011) investigated the microstructural evolution of an AZ31 Mg alloy sheet during dynamic deformation ($\sim 10^3$ s^{-1}) at RT.

Polycrystal modeling of Mg alloys is a helpful tool to explain the mechanical responses and deformation mechanisms in polycrystalline aggregates under different loading conditions. A visco-plastic self-consistent (VPSC) polycrystal model has been successfully applied to predict the evolution of twinning and texture during plastic deformation (Agnew and Duygulu, 2005; Yi et al., 2006; Jain and Agnew, 2007; Choi et al., 2007; Choi et al., 2009; Wang et al., 2010; Ma et al., 2012). The VPSC polycrystal model is based on a homogeneous scheme that can be easily used to predict macroscopic mechanical responses and macrotexture evolution during plastic deformation. The crystal plasticity finite element method (CPFEM), which is based on an inhomogenization scheme, was developed to consider the heterogeneous deformation behavior of AZ31 Mg alloys (Staroselsky and Anand, 2003; Graff et al., 2007; Fernández et al., 2011). Furthermore, microstructure-based CPFEM has been applied to simulate the micro-mechanical behaviors in a polycrystalline AZ31 Mg alloy under uniaxial loading (Choi et al., 2010, 2011; Shin et al., 2012). The CPFEM captured the heterogeneity of the stress concentration as well as the slip and twinning activities of a polycrystalline AZ31 Mg alloy under uniaxial compression.

The objective of the present study was to present a comprehensive set of results under a wide range of temperatures and strain rates and to investigate mechanical responses and deformation mechanisms under the simple shear and dynamic (tension and compression) deformations of AZ31 Mg alloy sheets. Texture measurements were performed on specimens after testing to measure the evolution of the initial texture during simple shear deformation under quasi-static loading and dynamic compression. Finally, a VPSC polycrystal model was used to simulate the evolution of the initial texture in an AZ31 Mg alloy sheet during simple shear deformation and dynamic compression.

2. Experimental procedure

Dynamic tension ($\sim$400 s^{-1}) and dynamic compression ($\sim$1500 s^{-1}) were performed on an AZ31 alloy sheet (3 wt%Al, 1 wt%Zn, Mg bal.), which was tested at room and elevated temperatures along RD, TD, and 45° to RD (DD). Dynamic compression ($\sim 10^3$ s^{-1}) experiments were also conducted with loading that was normal to the sheet plane (ND). Neutron diffraction and electron backscattered diffraction (EBSD) were used to measure the initial texture of the sheet sample and the deformed texture after simple shear and dynamic deformations, respectively. In previous studies (Khan et al., 2011), as-received material exhibited strong basal fiber texture and equal fractions of grains with the *c*-axis slightly tilted away from the sheet normal towards both +RD and −RD.