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Deformation behavior upon two-step loading in a magnesium alloy sheet

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ABSTRACT

Two-step loading tests were performed on an AZ31 rolled magnesium alloy sheet with strong basal texture in the normal direction, and the deformation behavior such as a stress–strain curve, Lankford value, and texture evolution was investigated both experimentally and numerically. When the sheet was subjected to compression in the rolling direction followed by tension in different directions, the following characteristic deformation was observed during the second loading: The sigmoidal shape of the stress–strain curve was more pronounced when the sheet was stretched in the rolling direction but less pronounced as the loading direction approached the transverse direction. The Lankford value during the second loading was much smaller than that of the virgin sheet. Observation of the microstructure showed that the detwinning activity during the second loading decreased as the loading direction approached the transverse direction. The aforementioned deformation behavior was qualitatively well predicted using a crystal-plasticity finite-element method. The crystal-plasticity analysis was then used to investigate the underlying deformation mechanism upon two-step loading, focusing especially on the effect of twinning and detwinning activities.

1. Introduction

Magnesium (Mg) alloy sheets are expected as possible lightweight materials for thin-walled structural components (Kulekci, 2008; Easton et al., 2008; Taub and Luo, 2015; Frankel, 2015), but their use is still low (Askari et al., 2014; Suh et al., 2015). One of the reasons that impede application of Mg alloy sheets is their deformation characteristics at room temperature, such as strain-path dependency (Hama et al., 2014, 2015a,b), tension–compression asymmetry (Lou et al., 2007; Hama et al., 2012; Nguyen et al., 2014; Kurukuri et al., 2014), anisotropic work hardening (Hama and Takuda, 2012a; Steglich et al., 2012), and nonlinear response during unloading (Hama and Takuda, 2011; Hama et al., 2013; Lee and Gharghouri, 2013,Wang et al., 2013a, Hama et al., 2015a). However, the details of these mechanisms are still open to discussion.

The strong characteristic deformation behavior of Mg alloys results primarily from the hexagonal close-packed (hcp) structure with significantly different critical resolved shear stresses depending on the slip and twinning systems. In particular, easy activation of direction-dependent deformation twinning affects significantly the mechanical behavior (Jiang et al., 2007; Knezevic et al., 2010; Fernández et al., 2013; Balík et al., 2016; Guo et al., 2016). Moreover, a strong basal texture generally develops in rolled sheets (Lou et al., 2007); thus, the anisotropy in deformation behavior is pronounced (Hama et al., 2014).

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Therefore, the deformation characteristics in rolled Mg alloy sheets are being actively studied to promote more effective use of Mg alloy sheets (Ghaffari Tari et al., 2014; Steglich et al., 2014). Thanks to recent advances in the modeling of twinning and detwinning, crystal-plasticity models are being widely utilized to study the macroscopic and mesoscopic deformation characteristics of Mg alloys (Proust et al., 2009; Hama and Takuda, 2011, 2012a, b; Oppedal et al., 2013; Wang et al., 2013a, b; Hama et al., 2013, 2015a, b; Liu and Wei, 2014; Wu et al., 2014; Li et al., 2014; Gu et al., 2014; Cheng and Ghosh, 2015; Qiao et al., 2015; Sánchez-Martín et al., 2015; Abdolvand et al., 2015; Dogan et al., 2015; Kabirian et al., 2015; Mayama et al., 2015).

Because sheet metals experience in general strain-path changes during forming processes, the work-hardening behavior under such changes is an important deformation characteristic. Two-step deformation is a representative deformation mode involving strain-path changes; thus, it has been studied extensively in various sheet metals. One of the typical examples of two-step loading is reverse loading, where the angle between the first and second loading axes, θ, is zero but the loading directions are opposite. Strong strain-path dependency occurs when Mg alloy sheets are subjected to reverse loading, as mentioned earlier. A sigmoidal curve occurs under tension following compression, whereas such a curve does not occur under compression following tension (Lou et al., 2007; Hama et al., 2012; Nguyen et al., 2014; Kurukuri et al., 2014; Hama et al., 2015b). Recently, it was reported that this strong strain-path dependency occurs not only in rolled sheets with strong basal textures but also in cast sheets with random crystallographic orientations (Hama et al., 2015b). The underlying mechanisms of this strain-path dependency have been studied extensively, in particular with respect to the effect of twinning and detwinning (Lou et al., 2007; Proust et al., 2009; Hama et al., 2012; Hama and Takuda, 2012b; Wang et al., 2013b; Wu et al., 2014; Nguyen et al., 2014; Kurukuri et al., 2014; Qiao et al., 2015), and it is now understood that one of the mechanisms is the activities of twinning and detwinning.

Concerning cases with $\theta \neq 0°$, the work-hardening behavior has been studied widely in face- and body-centered cubic metals such as steel and aluminum alloy sheets both experimentally and numerically (Kim and Yin, 1997; Teodosiu and Hu, 1998; Hoc and Forest, 2001; Peeters et al., 2001; Hahm and Kim, 2008; Holmedal et al., 2008; Rauch et al., 2011; Wang et al., 2012; Segurado et al., 2012; Gérard et al., 2013; Kitayama et al., 2013; Barlat et al., 2013; Mánik et al., 2015). For Mg alloys, on the other hand, a few studies on two-step compression tests have recently been reported. Sarker and Chen (2014) conducted a test of precompression in the extrusion direction (ED), followed by compression in the normal direction (ND) in an extruded AM30 Mg alloy with a strong basal texture in the ND, and they investigated the work-hardening behavior such as yield strength, ultimate compressive strength and the twinning activities, including secondary twins and detwinning. Xu et al. (2014) studied the generation of $\{10\bar{1}2\}$–$\{10\bar{1}2\}$ double twins and their effect on work-hardening behavior under precompression in the rolling direction (RD), followed by compression in the transverse direction (TD) in a hot-rolled AZ31 Mg alloy sheet with a strong basal texture in the ND. Shi et al. (2015) also examined the generation and role of $\{10\bar{1}2\}$–$\{10\bar{1}2\}$ double twins under precompression in the RD, followed by compression in the TD in a hot-rolled commercial AZ31 alloy sheet with a strong basal texture in the ND. It is evident from the abovementioned examples that most of the previous studies for Mg alloys have focused primarily on twinning activity and its effect on work-hardening behavior (Sarker et al., 2014; Xin et al., 2014, 2015; Park et al., 2015).

The deformation behavior during the second loading in two-step compression would be governed by both twinning and detwinning, as described in the abovementioned studies. On the other hand, it is expected that the deformation behavior during the second loading may be governed primarily by detwinning when Mg alloy sheets are subjected to two-step compression–tension, i.e., compression in the first loading, followed by tension along different directions in the second loading. Therefore, the deformation behavior would be notably different between two-step compression and two-step compression–tension. However, in contrast to two-step compression, the deformation behavior under two-step compression–tension has hardly been investigated. To the best of our knowledge, Park et al. (2013a) first studied the deformation characteristics of a hot-rolled AZ31 Mg alloy plate with a strong basal texture in the ND under two-step compression–tension. They investigated experimentally the deformation behavior under compression in the RD followed by tension or compression in the RD, the TD, and at 45° from the RD, and they found that the detwinning activity decreased as the second loading direction approached the TD. Moreover, they presumed that slip and twinning activities in the twinned region during the second loading would yield pronounced anisotropic deformation behavior. Because their study focused on twinning activity, a further effort is required to understand macroscopic deformation behavior such as yield stress and work hardening. Moreover, rectangular-shaped specimens were utilized in their study; thus, changes to the Lankford value, which is an important measure in sheet metal forming, upon the two-step loading were not investigated. Because twinning and detwinning activities affect the thickness strain in rolled Mg alloy sheets with strong basal texture, it is expected that the Lankford value would change significantly upon two-step loading. However, such results have not been reported yet.

It should also be mentioned that, unlike cubic metals, a theoretical model of the deformation behavior under two-step loading in Mg alloys has scarcely been studied except for reverse loading. Very recently, Wen et al. (2015) conducted two-step tension tests on a rolled Mg alloy sheet with a strong basal texture in the ND and investigated the mechanical behavior, including the stress–strain curve and evolution of the Lankford value. A dislocation density-based crystal-plasticity model was also used to discuss the deformation mechanism. Note that the twinning activity was negligible in their tests, and detwinning was in fact neglected in their model. As far as we know, simulation of the deformation behavior upon two-step loading with $\theta \neq 0°$, where the activities of twinning and detwinning are significant, has not been reported.

In the present study, the deformation characteristics of a rolled AZ31 Mg alloy sheet under two-step loading was investigated both experimentally and numerically. The sheet was subjected to tension or compression along the RD in the first loading, followed by tension along different directions in the second loading. The mechanical behavior, including