Computational Materials Science 132 (2017) 81–91

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Discontinuous yielding in wrought magnesium

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ARTICLE INFO

Article history:
Received 29 November 2016
Received in revised form 7 February 2017
Accepted 12 February 2017

Keywords:
Magnesium
Lüders
Twinning
Twin variant
Discontinuous yielding
Crystal plasticity

ABSTRACT

Recent reports of discontinuous yielding in the uniaxial compression of extruded magnesium suggest that twinning is accompanied by a significant stress decrease in the parent grain, leading to corresponding stress concentrations. We performed crystal plasticity finite element simulations using a simple twinning implementation that includes this "softening" effect for tensile twinning. With this method we were able to reproduce the experimentally observed yield point elongation and the Lüders-like propagation of strain and twinning over the sample. Twin variant selection was analysed in detail at various stages of deformation. Although lower rank variants were found to be activated, most of the twinning activity occurred on variants with the highest global Schmid factor. The stress fluctuations arising from the stress relaxation due to twinning did not appear to alter the dominance of the highest Schmid factor variant significantly. However, when twin softening is included, the twinning strain is dominated by a single variant. Despite giving rise to the highest stress fluctuations during yielding, simulations using the twin stress relaxation implementation actually showed less heterogeneity in stress after yielding. The results of our simple model suggest that "twin softening" could be key to the development of discontinuous yielding in extruded magnesium alloys.

1. Introduction

Mechanical twinning plays an important role in the plastic deformation of magnesium and its alloys due to the limited number of easily activated independent slip systems. In most magnesium alloys, after basal slip, tensile twinning on the $\{10\bar{1}2\}$ plane is the deformation mode with the lowest critical resolved shear stress (CRSS). In many deformation conditions, e.g. compression in the sheet plane of rolled sheet or compression along the extrusion direction in an extrusion sample, tensile twinning is responsible for the majority of plastic strain at low applied strains [1–3]. Under these conditions, twinning is expected to significantly affect yielding and immediate post-yielding behaviour. A sound understanding of the deformation of magnesium alloys requires, therefore, an accurate picture of how tensile twins nucleate and propagate. The twinning behaviour at yielding will strongly influence the stability of deformation at later stages. Macroscopically, it will affect the work hardening rate which determines uniform elongation in tension. Microscopically, twins play a part in introducing local stress heterogeneities, which might limit ductility during biaxial deformation.

In this article we use a crystal plasticity finite element framework to investigate the effect of twinning on the development of local deformation and stress heterogeneity during plastic deformation of magnesium. The aim is to explore the effects of relative twin to slip activity and the possible effects of a "softening" rule for twinning.

Twin variant selection can be used as an indicator of the magnitude of stress fluctuations present in the material during plastic deformation, caused by the interaction of elastically and plastically anisotropic grains. Experimental studies of twin variant selection generally rely on the statistical analysis of EBSD data. In [4–8] large deviations were found from the twinning behaviour expected from simple Schmid factor considerations. An extreme example of such deviations is [4], where a magnesium AZ31 rolled sample was compressed to 5% along the transverse direction. No relationship was found between the observed volume fraction of a twin variant and the Schmid factor of the given variant. In [5] high-purity zirconium was deformed under similar conditions. Strong non-Schmid behaviour was found for twin nucleation and almost no correlation for twin thickness and Schmid factor. In contrast, Barnett et al. [1,9] have recently reported "well-behaved" tensile twinning in a

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http://dx.doi.org/10.1016/j.commatsci.2017.02.010
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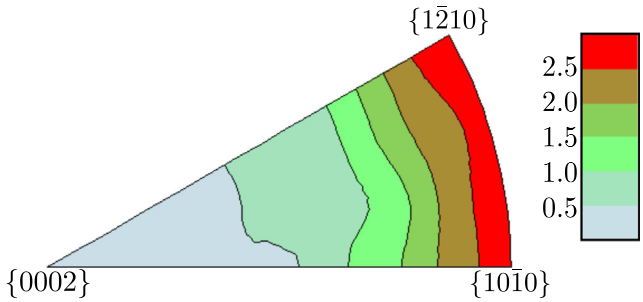

Fig. 1. Initial texture used in all simulations. Reference direction is ED (X direction in the simulation coordinate system.)

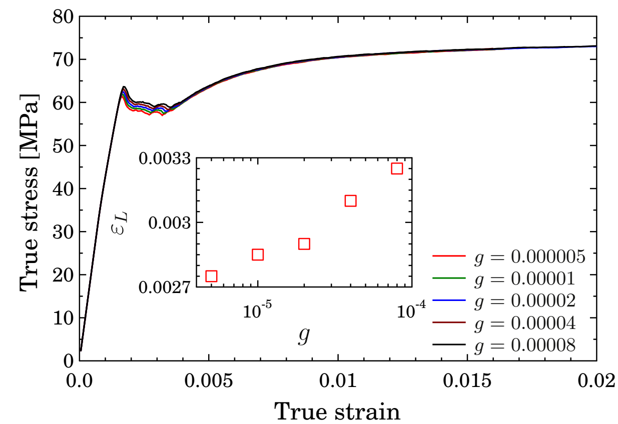

Fig. 3. Stress-strain curves for different values of the decay scale parameter g. Inset: dependence of yield elongation on g.

Table 1
CRSS values for the slip/twin modes used in the simulations. Values are given in MPa. Simulations *A* and *B* had constant CRSS values for twinning, while in Simulation *C* it was reduced from 45 MPa to 15 MPa, according to Eq. (2).

CRSS values (MPa)	Basal slip	Prismatic slip	Tensile twinning
Simulation *A*	15	75	45
Simulation *B*	15	75	15
Simulation *C*	15	75	45 → 15

detailed statistical analysis of EBSD data obtained from the uniaxial compression of an extruded magnesium AZ31 sample along the extrusion direction. This difference in the twinning behaviour could be caused partly by the difference in microstructure: "well-behaved" twinning was observed for fine grained specimens (mean grain size of $\approx 10\,\mu m$) whereas the strong non-Schmid twinning behaviour was mainly observed for coarser grains and a wider distribution of grain sizes. Wider grain size distributions will probably cause higher stress fluctuations at grain boundaries, leading to stronger deviation from the behaviour expected from Schmid factor considerations. An example of the importance of grain sizes and grain boundary irregularity can be seen in [10] where crystal plasticity finite element (CPFE) simulations systematically underestimate the non-Schmid behaviour of tensile twinning observed in the experiments. CPFE models are likely to provide more accurate predictions for fine grained materials and narrow grain size distributions.

Recently, Lüders-like deformation and the corresponding yield point elongation have been reported in [2,3] for fine grained AZ31 and ZM20 magnesium alloys. It is suggested that the cause of this phenomenon is the stress relaxation occurring in twinned grains, and the consequent concentration of stress at the twin tips. These stress concentrations lead to a higher probability of twin nucleation in neighbouring grains. This twin triggering effect is believed to be responsible for the Lüders-like propagation of deformation and twinning. This explanation assumes that once a twin nucleates, the growth of the twin occurs at a lower stress. Recent modelling work has shown that softening is important to the formation of twin bands in single crystals and to the propagation of twinning between neighbouring grains with high misorientations [11]. Twin softening provides the local stress drop, analogous to dislocation unpinning in steels, that is required for Lüders-like yielding [12–16].

In recent years, the EPSC model [17] has been used to successfully predict macroscopic stress-strain behaviour [17–20] and certain aspects of lattice strain evolution [18,19] in magnesium, while the VPSC model [21] has proved successful in predicting texture evolution [21–25] and twin volume fraction [22,25]. Although these mean field models have proved capable of accounting for many important aspects of deformation, they lose their validity when the phenomena in question depend significantly on local fluctuations of stress and strain. In such situations full field models have a clear advantage, even though the numbers of grains considered are generally lower due to the increased computational cost.

In this work we employ a crystal plasticity finite element model (CPFEM) to study the role of basal slip and twinning in the yielding behaviour of extruded magnesium in uniaxial compression. We

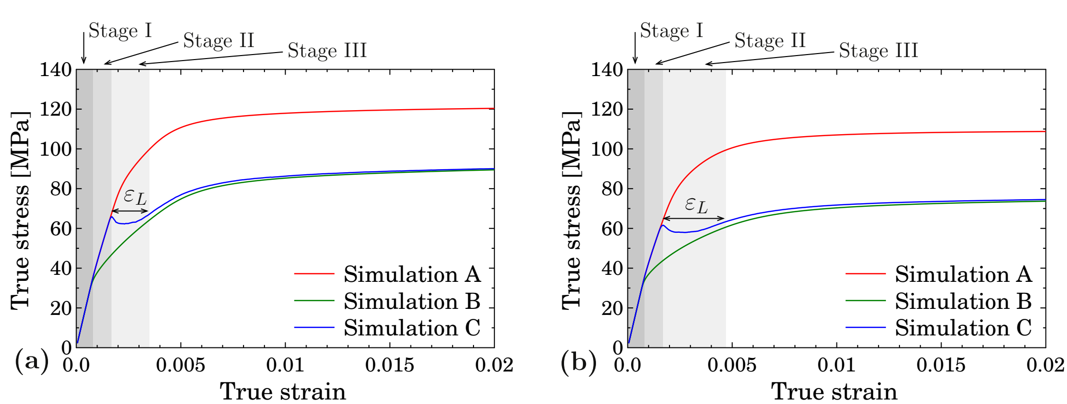

Fig. 2. Stress-strain curves for all three simulations in *Set 1* (a) and *Set 2* (b).Yield elongation is shown denoted by ε_L in both cases. Stage I: elastic region, Stage II: basal slip region, Stage III: tensile twinning region.