Acta Materialia 129 (2017) 149–158

Contents lists available at ScienceDirect

Acta Materialia

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

Full length article

Simulating strain localization in rolled magnesium

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A R T I C L E I N F O

Article history:
Received 30 November 2016
Received in revised form
7 February 2017
Accepted 13 February 2017
Available online 20 February 2017

Keywords:
Finite element method
Crystal plasticity
Magnesium
Localization
Computational mechanics

A B S T R A C T

The objective of this work was to computationally predict the interplay between material orientation, loading conditions, ductility, and failure behavior in samples hypothetically cut from a rolled plate of magnesium alloy AZ31B. Marciniak and Kuczyński analysis was used to predict failure by performing detailed finite element simulations in which imperfections are introduced at various angles to induce failure. Magnesium was represented by a reduced-order crystal plasticity model that has been shown to fit measured mechanical behavior, but is computationally efficient enough to be used in large-scale simulations and parametric studies. Plane strain tension simulations were performed on a range of material orientations, then forming limit diagrams were constructed for two selected orientations. Plane strain tension simulations indicate that for orientations where basal slip is active, the failure plane closely aligns with the basal plane. Additionally, the highest ductility was achieved by maximizing the amount of basal slip and equalizing the amount of extension twinning and non-basal slip. In magnesium, failure behavior is shown to strongly correlate with material orientation and the relative activity of deformation mechanisms. Comparison of the two forming limit diagrams highlighted the deficiency of using a single measure for ductility: although these orientations possessed similar strain to failure under plane strain tension this did not correlate with ductility under more complex loading conditions.

1. Introduction

Magnesium alloys have the potential to replace other lightweight metals due to their high strength and low density (1.74 g/cm^3). However, many magnesium alloys have shown a propensity for strain localization and failure, and exhibit relatively low ductility compared to other lightweight structural metals with comparable specific strength, e.g., high-strength aluminum alloys. Macroscopically, magnesium exhibits pronounced plastic anisotropy, wherein the material's initial yield strength and subsequent strain hardening rate strongly depends on how the loading direction relates to the material's processing directions, which is thought to limit its ductility. The plastic anisotropy is due to the inelastic behavior of prevalent deformation mechanisms, which themselves possess disparate initial strengths and subsequent hardening rates. Altering microstructural features such as grain size, alloy content, and precipitate distribution through thermomechanical processing has been shown to influence ductility in a secondary role; however, modifying bulk texture and its relation to principle loading directions is the dominant characteristic that governs ductility in magnesium alloys [1–9].

Processing methods used to improve tensile elongation to failure by modifying bulk texture in magnesium can generally be classified into two methods: (i) those that decrease peak texture intensity and (ii) those that reorient the macroscopic texture. By adding rare earth elements to magnesium, the c/a ratio is reduced and can approach that of an ideal hexagonal close-packed (HCP) crystal, e.g., $c/a = 1.624$ [10]. The increased crystal symmetry has been shown to reduce peak texture intensity during processing, which produces a material that exhibits reduced plastic anisotropy and increased tensile elongation to failure [5,11,12]. However, this increased tensile elongation to failure does not necessarily translate to increased ductility under other loading conditions, such as during deep drawing [13]. Peak texture intensity reduction has also been shown to occur during non-equilibrium process methods such as rapid solidification. In the spinning water atomization process (SWAP), fine powders were created via SWAP and subsequently extruded to produce magnesium alloys with fine grains (1–2 μm), low peak texture intensity, and moderate tensile elongation prior to failure [7]. Unlike the previous two methods, equal

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http://dx.doi.org/10.1016/j.actamat.2017.02.043
1359-6454/Published by Elsevier Ltd on behalf of Acta Materialia Inc.

channel angular extrusion (ECAE) produces peak textures that result in an equal or greater intensity than conventional forming processes, which are reoriented with respect to the original material's texture. Several ECAE routes have been shown to produce materials with superior strength and similar or improved elongation to failure over conventionally rolled or extruded alloys [1,8,9]. Similar macroscopic texture reorientation can be achieved during friction stir processing, which creates a strongly reoriented texture in the process zone that gradually decreases in regions away from the affected region. For processing methods that reorient the texture but do not reduce peak intensity, gains in elongation to failure are achieved because the peak texture and sample directions no longer coincide. However, if samples are cut from the as-processed material so that they are loaded along their principal texture components instead of material processing directions, large reductions in tensile elongation prior to failure have been observed [8]. Because a measure of ductility is strongly dependent on the interplay of texture and loading directions, it is desirable to develop an analytical or computational framework that can be used to find the optimal texture that maximizes ductility for a given set of loading conditions.

Defining a specific value for the ductility is difficult either from experimental viewpoint or as a mathematically derived quantity. Ductility is often referred to for a specific problem of interest, and may include quantities such as deep drawing ratio, minimum bend radius, or elongation prior to failure. The most commonly used quantity is tensile elongation prior to failure. In quasistatic, uniaxial tension tests, a variety of easy-to-interpret macroscopic ductility measures are commonly used. For ductile materials, the critical strain for Considère's criterion, $\varepsilon_c = d\sigma/d\varepsilon = \sigma$, is less than the strain corresponding to the ultimate tensile stress $\varepsilon_{max} = d\sigma/d\varepsilon = 0$, which is less than the total strain to failure, ε_f; yet, all three of these are reasonable measures of ductility for this simple loading case. Physically, localization in the specimen can occur due to geometric thinning or necking, material softening, imperfection-induced localization, or a combination thereof, and does not necessarily correspond to any of the aforementioned strain measures. For more complex loading cases, such as multiaxial deformation or dynamic loading, effects such as hydrostatic pressure and inertial effects also influence ductility.

Most analytical or computational theories identify the onset of localization following arguments of bifurcation or non-uniqueness; however, they differ in how the instability itself is initiated. Bifurcation theory originates from the concept that "stationary discontinuities" act as localization sites in the material. Alternatively stated, localization occurs in a band of material if the traction rate acting on the band is stationary with respect to extension and shear within the band [14]. Hill analyzed localization in elastic-plastic solids [15] then Rice [14] extended this work to analyze pressure-sensitive materials, cross-slip in single crystals, and vertex yield effects. Although this method is useful and has received significant attention in literature, failure in ductile materials has also been shown to occur both prior to, and after such conditions have been met [16]. Marciniak and Kuczyński (MK) analysis differs in that it assumes failure occurs by concentrations of strains initiated at imperfections[1] and identifies the failure strain as the value where the strain rate in the imperfection and bulk material diverge [16–18]. MK analysis was initially used to identify the failure strains for biaxial loading in sheet metal by specifying a thinned region with fixed angle relative to the loading directions. Hutchinson and Neale [19] extended this analysis to include that the imperfection may lie on an arbitrary angle with respect to the loading axis, and analyzed this for plane strain as well as general loading cases. This method has also been used to analyze single crystals as well as polycrystalline ensembles [20].

In this work, we analyze the correlation between material orientation and failure in rolled magnesium samples by performing full finite element simulations of MK specimens. Initially, we analyze a broad range of textures undergoing plane strain, uniaxial tension at moderate loading rates to determine how texture dictates failure under a single loading condition. By using a reduced-order polycrystalline magnesium model, we are able to analyze all possible orientations with relatively little computational cost, yet retain microstructural information to relate failure strains to activity of different deformation mechanisms. Then, we create forming limit diagrams (FLDs) for two polycrystalline textures that possess similar predicted failure strains to understand how ductility determined from uniaxial data relates to ductility under more complex loading conditions.

2. Methods

2.1. MK analysis

This analysis closely mirrors that by Hutchinson and Neale [19] in that we introduce a groove of material with angle θ that is inclined with respect to the loading direction. The groove has a reduced thickness compared to the surrounding region. Unlike previous work, a full finite element description is retained within the groove as well as the surrounding region. The mean strain rate within the groove is compared with the bulk to determine the limiting strain, e.g., the onset of strain localization. Strain localization is defined to occur when volume-averaged plastic strain rate inside the grooved region is 10 times that in the bulk, a ratio that has been used in previous studies [21]. Varying this ratio alters the total strain to failure in a straightforward manner, but does not influence qualitative trends. The plastic strain rate is calculated for a volume within the grooved region and for volumes above and below the grooved region, where care was taken to define the volumes to avoid elements close to surfaces.

Abaqus/Explicit 6.10 was used for all of the simulations in this study [22]. The consistent units used for Abaqus in these simulations are given in Table 1. The geometry of the rectangular bar specimens with a groove are shown schematically in Fig. 1. The groove is used to represent a hypothetical defect that exists in the material and could initiate a local instability. Tensile loading is applied in the y-direction. The specimens contained between 20,000 (0°) and 30,420 (60°) hexahedral elements (type C3D8RT) depending on the groove angle. The overall dimensions of the specimens are 10.0 mm tall, 2.0 mm wide, and 1.0 mm thick, with a 1.0 mm groove height for all simulations. The applied strain rate in all cases is 100.0 s^{-1} and all simulations are run to a maximum

Table 1
Consistent units used in Abaqus for this study.

Quantity	Units
Length	μm
Force	μN
Mass	ng
Time	μs
Stress	MPa
Energy	pJ
Density	ng/μm^3

[1] Imperfections may be descriptions of real physical imperfections or as surrogates used to mimic the effect of imperfections throughout the material. Although imperfection size and magnitude may affect quantitative measurements of ductility, it often does not affect qualitative trends.