Acta Materialia 133 (2017) 367–379

Contents lists available at ScienceDirect

Acta Materialia

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

Full length article

How magnesium accommodates local deformation incompatibility: A high-resolution digital image correlation study

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A R T I C L E I N F O

Article history:
Received 10 March 2017
Received in revised form
19 May 2017
Accepted 20 May 2017
Available online 20 May 2017

Keywords:
Magnesium
Strain distribution
Electron backscattered diffraction (EBSD)
Slip
Deformation twinning
High-resolution digital image correlation (HRDIC)

A B S T R A C T

The plastic deformation of single crystal magnesium is strongly anisotropic. This gives rise to deformation incompatibilities between grains during polycrystalline deformation, which are thought to limit ductility and formability. Wrought polycrystalline magnesium alloys are far from brittle, especially in uniaxial tension, implying that these incompatibilities can be accommodated to some extent, although it is not clear how. We have used high-resolution digital image correlation (HRDIC), supported by electron backscatter diffraction (EBSD), to study quantitatively and at the microstructural scale the accommodation of deformation incompatibility in an AZ31 magnesium alloy. Using a new gold remodelling procedure that improves the spatial resolution to 44 nm, we quantified the deformation heterogeneity after a small stretch in uniaxial tension. Our results confirm that polycrystalline deformation is very heterogeneous, with local axial true strains at grain boundaries 32 times higher than the applied average strain of 0.027, and 18 times higher at slip bands within grains. The local and macroscopic deformation gradients are very different in character as well as magnitude. The resultant deformation incompatibility is accommodated primarily by gradients in basal slip and the activation of difficult slip in "hard" grains, giving rise to grain breakup, with a smaller contribution by enhanced grain boundary shear and twinning. These results support the idea that a homogeneous distribution of "hard" and "soft" grains can prevent the development of strain localization and, therefore, that controlling texture and microtexture is a powerful way of enhancing the formability of magnesium alloys without reducing their single crystal plastic anisotropy.

1. Introduction

Magnesium alloys offer the greatest lightweighting potential of all structural alloys that if fully exploited would revolutionize transport efficiency. However, poor corrosion resistance, ductility and formability hamper this potential and limit their exploitation. There have been recent breakthroughs in corrosion resistance [1,2], and new rare earth containing alloys have much improved ductility [3–5]. However, we still do not understand what fundamentally limits the formability of magnesium alloys. It is fair to say that the recent improvements owe more to empiricism and serendipity than to increased scientific understanding.

The deformation of magnesium has been studied extensively and the basic deformation mechanisms are well known. Experiments have shown that magnesium and its alloys deform mainly by easy basal slip, whilst other slip modes are much more difficult to activate [6–8], making the plastic deformation of single crystals strongly anisotropic. The reasons for this anisotropy have been recently explained by Wu and Curtin [9] who that showed the ⟨c+a⟩ dislocation undergoes intrinsic dissociation into basal-dissociated immobile dislocation structures. Similar processes seem to be explain why basal slip dominates in magnesium but not in other hexagonal metals like titanium and zirconium [10]. In addition to slip, magnesium alloys also deform extensively by twinning, which can accommodate some of the strain slip cannot. However it is unclear whether twinning contributes significantly to ductility or formability, because of the complex way in which it transforms the microstructure and interacts with slip.

It is often stated that magnesium has low ductility because there are not enough easy slip systems to fulfil the von Mises or Taylor criterion for uniform deformation, implying that ductility can only

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http://dx.doi.org/10.1016/j.actamat.2017.05.040

be improved by reducing slip anisotropy [11]. However magnesium alloys are far from brittle, despite their extreme slip anisotropy. Although magnesium alloys deform primarily by basal slip they achieve elongations to failure of 20–30%. How does twinning contribute to these elongations? What is the role of grain boundary shearing? Answering these questions could help develop new, more formable alloys, whilst accommodating their inherent and difficult to change anisotropy.

The ability to achieve reasonable ductility at room temperature, primarily by basal slip, implies that the deformation of magnesium polycrystals is non-uniform and that this deformation heterogeneity is somehow accommodated. For this to happen, accommodation processes must enable the grains to deform differently but cooperatively, in an almost self-organized manner, combining to give the uniform behaviour observed at the macroscale. There are several suggestions for what these processes might be, including the activation of difficult slip systems [12,13], twinning [14,15] and even grain boundary shearing [16,17]. Of these mechanisms, twinning has perhaps been the most comprehensively studied, in great part because its crystallographic character makes it particularly suited to the electron backscatter diffraction (EBSD) technique. There have been a great number of EBSD studies of twinning in magnesium (e.g. Refs. [18–21]), often alongside in-situ diffraction work [22,23] and crystal plasticity modelling [24–26]. However, in the context of deformation incompatibility these studies are contradictory. If twins played a significant role in accommodating local deformation incompatibilities, one would expect their distribution to be dictated by local stress fluctuations, as evidenced by some researchers [27]. However, a number of studies have also shown that most twins can be explained by simply considering the orientation of their parent grains [28].

Using EBSD to fully understanding the role the different possible accommodation mechanism is difficult because whereas it is ideal for study twinning, its abilities are limited when it comes to studying slip or grain boundary shearing. Although high-resolution EBSD can be used to extract values of geometrically necessary dislocations (GND) density [29,30] and some slip activity can be inferred from misorientation axis analysis [31,32], it does not provide access to the deformation kinematics. EBSD cannot be used to quantify local plastic strain and therefore insights it provides into slip activity are indirect and sometimes ambiguous.

In this paper, we use high-resolution digital image correlation (HRDIC) to study quantitatively the deformation incompatibility in a magnesium alloy at the microstructural scale. The experiments presented here are a refinement of the procedure proposed by Di Gioacchino and da Fonseca [33], which has made it suitable for use with corrosion prone magnesium and has improved the spatial resolution without sacrificing coverage. These improvements have increased spatial resolution to 44 nm, whilst making it possible to cover an area 150 μm by 120 μm in size, covering about 30 grains. This is the equivalent of using $9 \cdot 10^6$ strain rosettes, each 44 × 44 nm in size. Our aim was to exploit this unprecedented capability to measure strain heterogeneity and, in combination with EBSD orientation mapping, to study quantitatively the mechanisms by which it is accommodated. By mapping deformation at this high spatial resolution we were able to quantify grain boundary shearing, determine slip activity and how it is affected by twinning, and how grains are broken up by twinning and slip.

2. Experimental method

2.1. Sample preparation

The material studied was an AZ31 (2.81 wt % Al, 1.22 wt % Zn, 0.26 wt % bal. Mg) magnesium alloy, in the form of 1 mm thickness sheet. Dog-bone tensile samples with 20 mm gauge length, 5 mm gauge width and 1 mm thickness were electro-discharge machined. In order to obtain a homogeneous microstructure free of twins, the samples were subjected to a recrystallization treatment conducted at 345 °C for 1 h followed by furnace cooling. The samples were then ground to #4000 grit paper, polished with 3 and 1 μm oil-based diamond suspensions and finished with water-free fumed silica (0.2 μm) suspension for ~1 min.

The DIC technique requires a suitable pattern on the sample surface. In this study we develop a homogeneous and fine distributed gold speckle pattern by remodelling of a thin gold layer, previously deposited on the sample surface, using an in house styrene-assisted gold remodelling device. The gold layer was deposited using an Edwards S150B sputter coater for 2 min providing a ~25 nm thickness gold layer. Once the gold layer was deposited, the samples were placed in the styrene-assisted gold remodelling device shown schematically in Fig. 1. The process consists of flowing argon gas containing styrene vapour onto the surface of the gold-coated material that is positioned on a heated plate. This subsequently remodels the gold layer into fine speckles. The remodelling device is divided into four areas. The first area (Fig. 1a) provides control of the argon flow throughout the system, which then passes through a styrene reservoir in area 2 (Fig. 1b), turning into a mixture of argon and styrene vapour. The area shown in Fig. 1c provides control of the temperature of the hot plate positioned in the remodelling chamber in Fig. 1d. The sample is placed in the remodelling chamber (Fig. 1d) on a hot plate with a flat surface to give a good contact with the sample and assure a homogeneous temperature distribution throughout the material. The Ar-Styrene mixture is allowed to flow into the remodelling chamber directly over the sample surface. The warm gas then exits the remodelling chamber into the exhaust chamber and leaves the system. This two-chamber design assures that the sample is always in contact with fresh styrene flow. The optimum speckle pattern, which had a speckle size of ~20–30 nm was obtained after two

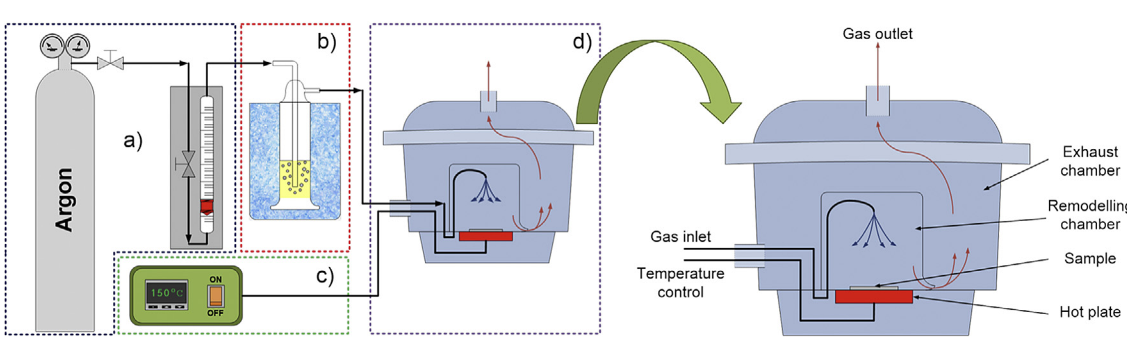

Fig. 1. Styrene-assisted gold remodelling rig. a) Argon flow control zone, b) styrene reservoir, c) temperature control unit and d) remodelling vessel.