Texture Evolution of AZ31 Magnesium Alloy Sheet at High Strain Rates*

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Abstract

In the current contribution the mechanical behaviour at high strain rates of AZ31 magnesium alloy sheet is studied. Uniaxial deformation properties were studied by means of tensile split Hopkinson pressure bar (SHPB) at different temperatures. The influence of the strain rate and temperature on the deformation mechanisms was investigated by means of electron backscatter diffraction (EBSD) and neutron diffraction. It is shown that twinning plays an important role on high strain rate deformation of this alloy, even at elevated temperatures. Significant evidence of prismatic slip as a deformation mechanism is observed, also at warm temperatures, leading to the alignment of <10-10> directions with the tensile axis and to a spread of the intensities of the basal pole figure towards the in-plane direction perpendicular to the tensile axis. The rate of decrease of the CRSS of non-basal systems is observed to be slower than at quasi-static rates. Secondary twinning and pyramidal <c+a> slip were also outlined for some conditions. At warm temperatures, in contrast to quasi-static range, a generalized dynamic recrystallization is not observed. Moreover, the activation of rotational recrystallization mechanisms is reported.

Keywords

High strain rate, Magnesium Alloy, Texture

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* *This work is based on the results of MAGNO2008 and MANUFACTURING 0,0 projects; the authors would like to thank Spanish Ministry and Basque Government for its financial support.*

1 Introduction

Magnesium alloys have been thoroughly studied in the last decades due to their low density and thus their potential to reduce weight of any structure. Even though large number of studies have been carried out on the plastic deformation behaviour of magnesium alloys, most of them have their focus on the materials response under quasi-static loading conditions (e.g. [1-10]). However, in some structural applications, components must be designed to operate over a broad range of strain rates and temperatures. For instance, the high strain rate behaviour is of great interest to automotive, aerospace and/or defence industries because some critical components should have the proper mechanical properties to work under severe loading conditions, such as crash or impact. Furthermore, in most metalworking processes, materials undergo large amounts of strain at different strain rate and temperature conditions. High strain rate deformations (in the order of 10^3 s^{-1}) are subjected to the materials in some innovative manufacturing methods such as in electromagnetic forming operations, owing to an increase in the forming limit as reported in [11] for Mg AZ31 alloy.

The mechanical behaviour and deformation mechanisms of magnesium and its alloys at low strain rates have been extensively investigated. Slip in hexagonal close packed (hcp) metals may take place along the <11-20> (<a>) direction, mainly on {0001} basal plane, but also on non-basal planes, such as {10-10} prismatic and {10-11} pyramidal planes. Additionally, second order pyramidal <c+a> slip has also been observed along {11-22} planes [2]. Deformation is also accommodated by twinning, mainly along {10-12} and {10-11} planes, so called extension and compression twinning respectively. Apart from single twinning, secondary twinning from a primary twin ({10-11} – {10-12}) was also reported in magnesium single crystals by Wonsiewicz and Backofen [4]. Recently, Barnett et al. [3] have also shown non-Schmid behaviour of this secondary twinning by EBSD and TEM investigations.

It is generally accepted (e.g. [2, 5, 6]) that at room temperature, slip on basal planes and {10-12} twinning are the main deformation mechanisms in uniaxial deformations at low strain rates. However, deformation temperature plays an important role in the activity of different deformation modes. The critical resolved shear stress (CRSS) for basal slip and {10-12} twinning is temperature independent [5]. Meanwhile, the CRSS for prismatic and pyramidal systems decrease with increasing temperature, even to smaller values than {10-12} twinning. Moreover, at temperatures higher than 200ºC dynamic recrystallization takes places simultaneously [7-9]. The activation of these additional mechanisms results in an increase of ductility and a decrease of yield and flow stress.

The low availability of independent slip systems makes Mg alloys highly dependent on texture [10]. It is further emphasized by the polarity of {10-12} twinning, which only allows shear in one direction (opposed to forward and backward shear in deformation by slip) [12]. When investigating rolled or extruded magnesium, as they develop strong texture during processing, the dependence of the initial texture on the deformation mechanisms and thus the mechanical properties is more pronounced. For example, a strong tension-compression asymmetry at low strain rates has been reported and related to texture.

The deformation behaviour of Mg alloys at high strain rates (10^3 s^{-1}) has not been thoroughly investigated yet [13-17]. Generally, it has been concluded that ductility increases with increasing the strain rate [13-15]. Additionally, twinning has been observed to significantly contribute to plastic deformation even at high temperatures, at which it is mostly suppressed at quasi-static strain rates. However, most of the studies carried out to date mostly dealt with extruded or casted Mg alloys and predominantly under compressive loading. Above all, the influence of temperature, loading condition (tension-compression) and texture on the deformation mechanisms and flow stress at high strain rates is still unknown.

In the current study, the uniaxial mechanical behaviour of AZ31 sheet under dynamic conditions (10^3 s^{-1}) was analyzed and compared with that observed at low strain rates. AZ31 sheets have been tested in tension and compression using Hopkinson bar apparatus from 25ºC to 400ºC. Detailed microstructure and texture examination by electron backscatter diffraction (EBSD) and neutron diffraction has been carried out to elucidate the predominant deformation and recrystallization mechanisms.

2 Experimental procedure

2.1 Initial material. Microstructure and crystallographic texture analysis

The initial material used in this study was the commercial-grade Mg alloy AZ31. Two rolled and annealed sheets, 1 and 3 mm thickness, were used.

The microstructure and texture of the as-received material was analyzed by electron backscatter diffraction (EBSD) employing EDAX-OIM™ software in a Zeiss Ultra 55™ FEG-SEM scanning electron microscope. Sample preparation for EBSD included grinding up to 4000 SiC paper, mechanical polishing with a 0.05 µm silica suspension and final electro-chemical polishing for 90 s at 33 V using the AC2™ commercial electrolyte. The microstructure is presented by EBSD orientation maps and the texture by recalculated pole figures. Since EBSD only allows examination of the local texture, macrotexture measurements were also performed by means of neutron diffraction in the Stress-Spec instrument from FRM-II of the TU-Munich (Germany) with a beam size of 5 mm diameter.

The initial microstructures of the two AZ31 sheets of 1 and 3 mm thickness were formed of equiaxed recrystallized grains with average intercept sizes of 10 and 13 µm respectively (Figure 1). As generally observed in annealed AZ31 sheets, both sheets show strong basal type texture (i.e. crystallographic *c*-axes are aligned in the sheet normal direction). It can also be seen in the pole figure from Figure 1 that the <0001> fiber is not perfect and a spread of the basal poles toward sheet rolling direction (RD) is present. Neutron diffraction measurements were consistent with the EBSD measurements.

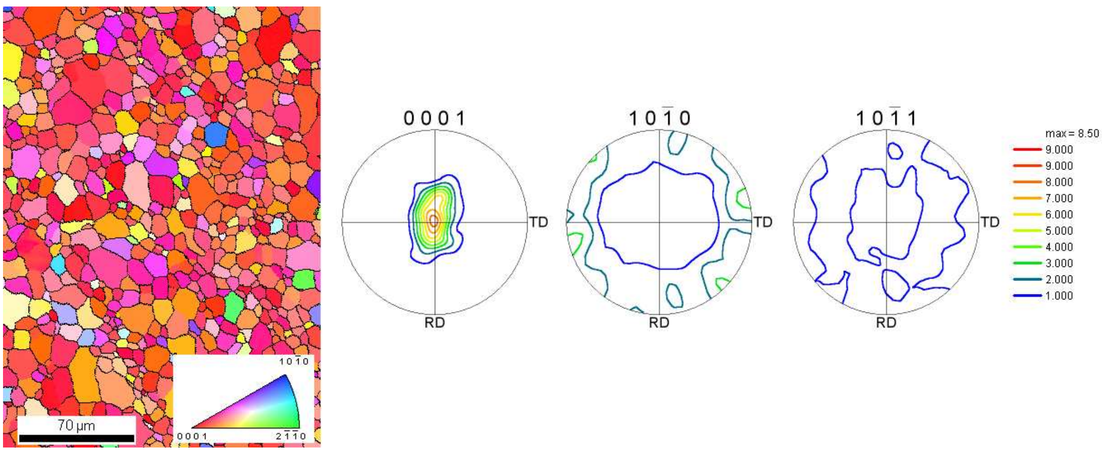

Figure 1*: Microstructure and texture of the as-received AZ31 Mg alloy measured by EBSD (The colour code corresponds to the normal direction -ND- inverse pole figure).*

2.2 Mechanical testing

An exhaustive testing campaign was performed in order to compare high strain rate with quasi-static behaviour at different temperatures. Tensile tests were performed on the 1 mm thick sheet. The reader is referred to [18] for more detailed description of the testing procedures. High strain rate tests at $10^3\ s^{-1}$ were carried out using a tensile split Hopkinson bar. A radiative furnace was used for testing at several temperatures. Thermocouples were glued to both surfaces of the specimens to measure the initial temperature of the sample. Quasi-static tensile tests were carried out using a conventional INSTRON-4206 testing machine equipped with a heating furnace. The specimens tested at low strain rates were machined according to ASTM E8 M-0 standard. At both high and low strain rates, tests were performed along RD at temperatures ranging from 25ºC to 300ºC (In-plane RD-TD anisotropy in tension can be seen in [19]). Compression testing was performed on the 3 mm thick sheet. High strain rate compression tests at $10^3\ s^{-1}$ were carried out using a Hopkinson bar apparatus. At both high and low strain rates, tests were performed along RD and ND at temperatures ranging from 25ºC to 400ºC. The specimens compressed along RD were 3 x 3 x 4.5 mm while the samples compressed along ND were 3 x 3 x 3 mm cubes (See [19] for the ND-RD anisotropy in compression).

The microstructure and texture of the samples deformed in tension were examined by EBSD and also by neutron diffraction (procedure explained above). Microstructural analysis of the samples deformed in compression could not be performed because the specimens were smashed during testing.

3 Results and discussion

3.1 Mechanical behaviour at high strain rates

Figure 2 shows true stress - true strain curves comparing tension-compression behaviour at different strain rate and temperature conditions. It is observed that at room temperature the shape of the curves is concave down under tensile loading and concave up under compressive loading. The tension-compression asymmetry, generally observed at low strain rates and room temperatures, is maintained at high strain rates. These stress differences are consistent with the predominance of crystallographic slip in tension and {10-12} twinning followed by strain hardening in compression.

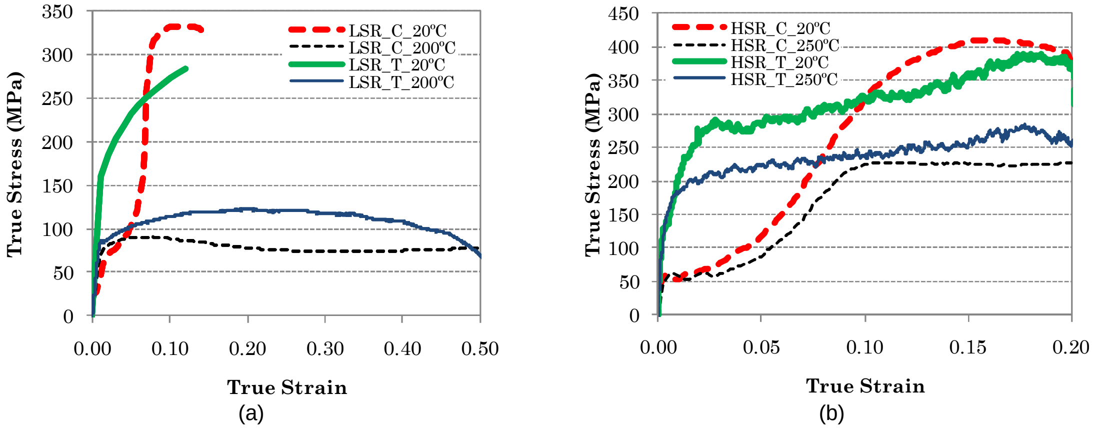

***Figure 2**: True stress – true strain curves showing tension-compression asymmetry at a) low strain rates ($10^{-3}\ s^{-1}$) and (b) high strain rates ($10^3\ s^{-1}$).*

At elevated temperatures, at low strain rates, the tension-compression asymmetry is significantly reduced as a consequence of the activation of non-basal slip systems in combination with the dynamic recrystallization (DRX) in both loading conditions. However, at high strain rates the asymmetry is still observed and a strain hardening behaviour is observed in contrast to the softening behaviour seen at low strain rates. Moreover, concave up curves have been obtained when testing in compression along RD at temperatures as high as 400ºC. It can also be confirmed from compression tests along ND that the CRSS for {10-12} twinning is strain rate independent.

3.2 Microstructure and texture evolution at high strain rates

The microstructure and texture of the different tensile samples are shown in Figure 3. The sample deformed at RT shows elongated grains in the loading direction with some twins, while dynamic recrystallized microstructure is observed after the quasi-static loading at 250℃. Interestingly, the strengthening of the text ure component corresponding to the alignment of the <10-10> direction in the tensile loading direction is observed in both samples evidencing the activity of prismatic slip. The intensity of the <10-10> poles parallel to the loading direction is decreased significantly in the sample deformed at 250℃ in comparison with that in the room temperature sample as a consequence of the generalized DRX as it observed in the microstructure.

At high strain rates, an increase of the amount of twins is observed, in comparison with quasi-static samples. Neutron diffraction analysis also shows a new texture component in the (0001) pole figure at high strain rates, not observable at quasistatic strain rates. This new component was associated with the increase of {10-12} tensile twinning activity which causes the grain rotate ~86º. Secondary twins are also observed in EBSD orientation maps by analyzing the boundary characters (Figure 4) in a significantly higher amount than at quasi-static samples. Moreover secondary twins are also observed at high strain rate and elevated temperatures. Finally, a splitting of the intensities in the basal pole figure is observed at 250ºC. This texture type can be developed by the activation of <c+a> pyramidal slip as it was previously suggested [20]. Additionally, secondary twinning could also contribute to splitting basal intensities as shown in Figure 4.

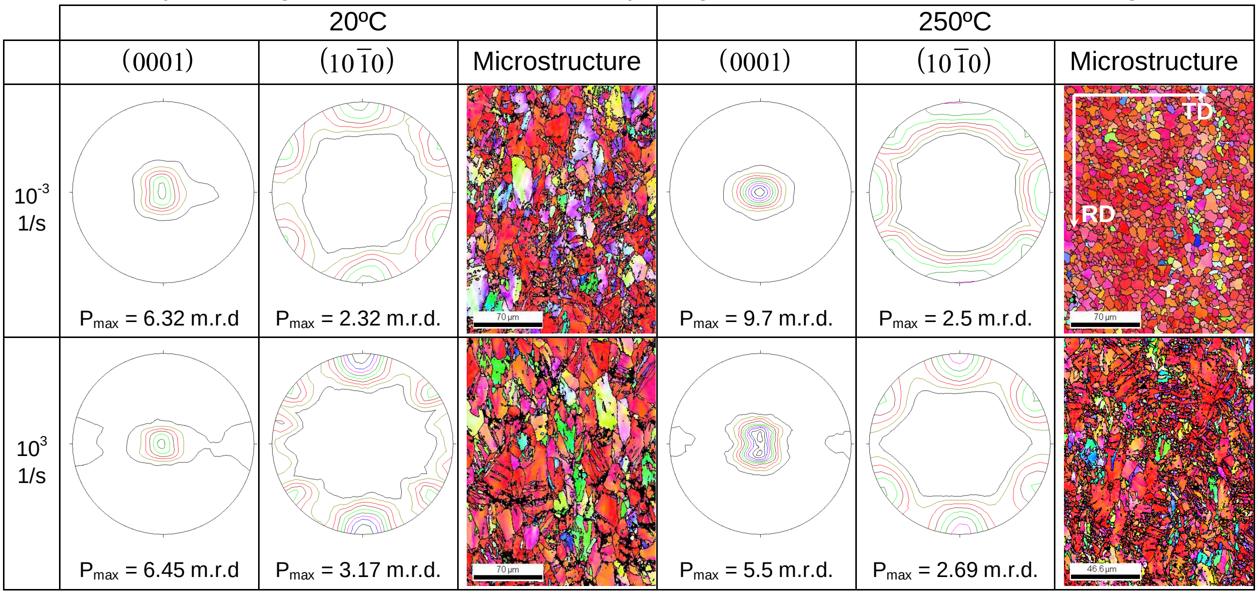

Figure 3*: Microstructure measured by EBSD (The colour code corresponds to the ND inverse pole figure) and macrotexture of the different samples.*

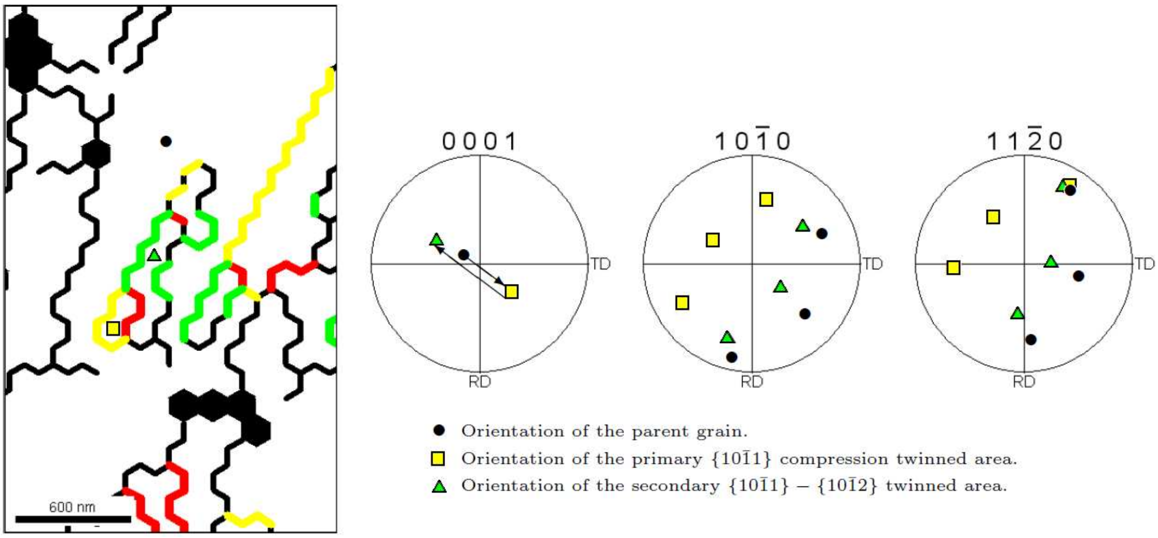

***Figure 4**: Example of a secondary twin formed and the orientations in the pole figures of the parent grain, primary compression twin and secondary tensile twin. The contribution of the secondary twinned area to the micro-textures with orientation between 0º and 90º towards the perpendicular of the loading direction (in this case RD) is visible.*

The dynamic recrystallization (DRX) mechanisms observed in Mg alloys can either be discontinuous (DDRX) or continuous (CDRX) [8, 21]. The first type consists on the nucleation of new grains and their growth and in the latter type new high angle boundaries are formed as a consequence of local lattice rotations by dislocation accumulation. Rotational dynamic recrystallization (RDRX) is a variation of the latter in which new grains are formed near grain boundaries due to increased dislocation activity as a consequence of intergranular strain incompatibilities [1, 8, 22]. Rotational dynamic recrystallization has been observed during high strain rate deformation of not only minerals [23] but also metals [24].

However, differentiating DDRX and RDRX mechanisms can be challenging, as in both cases the new grains usually develop near grain boundaries. For the particular case of rolled sheets of AZ alloys, it has been reported that recrystallized grains nucleated by DDRX usually possess a basal fiber [2, 25], whereas those formed by RDRX tend to have orientations in which *c*-axes are tilted away from the ND [22]. Results from the current study confirmed that when testing the AZ31 alloy in tension at 250ºC at low strain rates DDRX took place, as revealed by the development of basal fiber texture and strain free recrystallized grains (Figure 3). When testing at high strain rates and 250ºC, a small amount of recrystallized grains is observed in contrast to the generalized RX observed at low strain rates. In addition, clear divergences are observed in contrast to DDRX. Two observations suggest an increasing contribution of rotational recrystallization. Firstly, the KAM map in Figure 5 reveals that some small grains were not strain free. Secondly, in some small grains the *c*-axes were rotated away from the ND as it can be seen in Figure 5, where the orientation of several recrystallized grains is plotted using discrete pole figures. Finally, from these results, it is suggested that recrystallized grains may be formed by a combination of both DDRX and RDRX due to the limited time for diffusion.

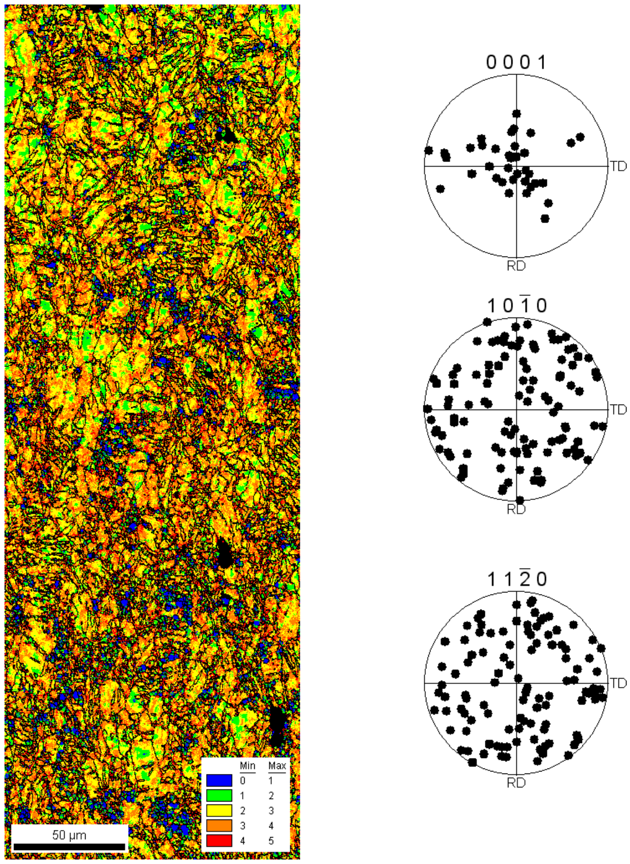

***Figure 5**: Kernel average misorientation (KAM) map and discrete orientations of the recrystallized grains of the sample deformed at high strain rates (10^3 s^{-1}) and 250ºC.*

4 Conclusions

The mechanical behaviour of AZ31 magnesium alloy has been investigated at high strain rates and compared to quasi-static data. Results from this study will be interesting to design parts for dynamic loading condition. The main conclusions are listed below:

1. With increasing temperature at low strain rates, the tension-compression asymmetry decreases and non-basal slip planes become active. However, at high strain rates, this asymmetry is retained at high temperatures and twinning remains active under these conditions.
2. Tensile twinning is enhanced at high strain rates compared with low strain rates. It remains being the predominant deformation mechanism during the early stages of deformation in compression tests even at elevated temperatures.
3. Alignment of <10-10> directions with the tensile axis was observed which evidences activity of prismatic slip at high strain rate deformation even at high temperatures.
4. {10-11} – {10-12} secondary twins were also observed in EBSD orientation maps in the sample deformed at high strain rates.
5. A splitting of the intensities in the basal pole figure is observed in the sample deformed at high strain rates and 250ºC. This texture type can be developed by the activation of <c+a> pyramidal slip. The importance of second order

pyramidal slip is not only because it can accommodate deformation along *c*-axis but also because on supporting 5 independent slip systems by itself.

6. A small fraction of recrystallized grains was observed in tensile samples deformed at high strain rates and 250ºC. It is suggested that rotational recrystallization is activated due to the limited time for diffusion at high strain rates.

Acknowledgements

Neutron diffraction measurements were supported by the EC under the 6th FP through the Key Action: Strengthening the ERA, Research Infrastructures. Contract no. RII3-CT-2003-505925. The authors would like to thank the vehicle interior manufacturer Grupo Antolin Ingeniería S.A. within the framework of the project MAGNO 2008-1028 CENIT funded by the Spanish Ministry.

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