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Influence of the processing of magnesium alloys AZ31 and ZE10 on the sheet formability at elevated temperature

Lennart Stutz[1, a], Jan Bohlen[1, b], Gerrit Kurz[1, c], Dietmar Letzig[1, d] and Karl Ulrich Kainer[1, e]

[1]Helmholtz Zentrum Geesthacht Zentrum für Material- und Küstenforschung GmbH, Max-Planck-Straße 1, 21502 Geesthacht, Germany

[a]Lennart.Stutz@hzg.de, [b]Jan.Bohlen@hzg.de, [c]Gerrit.Kurz@hzg.de, [d]Dietmar.Letzig@hzg.de, [e]Karl.Kainer@hzg.de

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Abstract. The substitution of conventional materials such as aluminium alloys and steels with the lightest structural metal magnesium and its alloys can yield significant weight saving in the transportation industry and hence, reduce vehicle weight and greenhouse gas emissions. Producing magnesium sheets by conventional hot rolling is expensive due to the large number of rolling passes to final gauge and annealing steps at elevated temperatures between the rolling passes. Twin roll casting is a well established processing route for aluminium sheets which can reduce the necessary rolling passes to a bare minimum to reduce the production costs. This process is receiving increasing attention for the production of magnesium sheets. This study reveals first hand results of sheet metal forming experiments on magnesium sheets rolled from twin roll cast strip as well as conventional DC cast slabs. Two different alloys, AZ31 (Mg-3Al-1Zn-Mn) and rare earth element containing ZE10 (Mg-1Zn-RE) were investigated. It is known that these alloys show significant differences in the microstructure development during conventional rolling as a result of recrystallisation. For hot rolled AZ31, distinct textures are formed with the majority of basal planes oriented in the sheet plane and hence, unfavourably for basal slip. Conventionally rolled ZE10 commonly shows a much weaker texture. Forming limit diagrams are presented and discussed with respect to the initial texture of the sheets. Strain response to various strain paths and plastic anisotropy are evaluated. Results of twin roll cast sheets are compared with conventionally hot rolled sheet of the same alloys. Competitive formability can be achieved at 200°C for all tested sheets. While conventionally rolled sheets show a generally higher formability than their twin roll cast counterparts, ZE10 outperforms AZ31 for both processing routes.

Introduction

Reducing vehicle weight and emissions by lightweight design is a major goal of the the automotive industry. Magnesium as the lightest structural metal bears a significant weight saving potential compared to steels and aluminium alloys [1,2]. Cast magnesium components are widely used e.g. as engine blocks or gear box houses. The application of magnesium sheets is currently hampered by two main obstacles. Conventional hot rolling from slabs requires several rolling passes and annealing steps, resulting in the high cost of magnesium sheets. Also, conventional magnesium sheets show limited formability at ambient temperature. Forming processes of components have to be conducted at elevated temperatures.

In order to overcome these obstacles, it is necessary to reduce the production cost of magnesium sheets and increase their formability. The main reason for the limited formability of magnesium sheets is the distinct basal type texture that is formed during hot rolling. This texture is characterised by the majority of the basal planes being oriented parallel to the rolling direction. Basal slip is the most important deformation mechanism in magnesium alloys. The unfavourable orientation of the basal planes results in low work hardening potential [3]. One approach to increase the formability is

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to change the texture to a more random orientation distribution. The addition of rare earth elements (RE) is known to reduce the texture intensity in aluminium-free wrought magnesium alloys [4,5]. Advanced alloys such as ZE10 (Mg-1Zn-RE) are expected to show higher formability in deep drawing and stretch forming conditions [3,6,7,8] but profound evaluation of formability under different forming parameters remains rare.

An alternative, cost efficient, processing route for magnesium sheets with improved properties is production of the feedstock by twin roll casting (TRC). This process is receiving increasing attention for the production of magnesium sheets. In the twin roll casting process liquid metal is pumped from a furnace or cast over a pipe into a tundish. The melt is then dragged into the roll gap of a pair of counter rotating, internally cooled rolls. The metal solidifies upon contact with the cooled rolls and is rolled to a strip. These strips can be rolled using conventional rolls in a continuous process. In the next production step the strip is rolled to final gauge by a rolling process.

Experimental

This study investigates the formability of conventionally hot rolled magnesium sheets and sheets rolled from twin roll cast strips. Two alloys were selected, AZ31-B (Mg-3Al-1Zn-Mn) as a conventional wrought magnesium alloy and the advanced rare earth element (RE) containing alloy ZE10 (Mg-1Zn-RE). In the case of conventionally rolled ZE10 sheet, a small amount of zirconium was present. Zirconium is a well known grain refiner in aluminium-free wrought magnesium alloys [9]. In the case of finer grained twin roll cast strips as precursor, an additional grain refiner was considered not necessary by the supplier. The nominal thickness of all sheets was 1.5mm and the sheets were provided in annealed temper. The initial texture of the sheets was measured with a Panalytical X-ray diffractometer setup. Cu K_α radiation was used and (0002) pole figures were recalculated from the orientation distribution function.
Quasi-static tensile tests were conducted at room temperature to determine the mechanical properties of the sheets. Specimens were cut from the sheets by spark erosion along the rolling direction (RD) and the transverse direction (TD). The technical strain rate was $10^{-3}s^{-1}$. The elongation of the specimens was measured by an extensometer and the tensile force was measured by a 50kN load cell.

To assess the formability, Nakajima type tests were conducted. The Nakajima test uses different specimen geometries in a common setup that all represent a different strain path. In the present study, specimen geometries according to Hasek [10] were tested. The specimens were round blanks of 200mm diameter with semi-circular recesses with diameters of 40 to 80mm. A hemispherical punch (d=100mm) deformed the clamped specimens until fracture at a punch speed of 60mm/min. Oiled PTFE blanks of 50µm thickness were used for lubrication between punch and specimen. Tests were conducted at room temperature and at 200°C with all components being preheated to the target temperature prior to testing. Local strain measurement during the Nakajima test was done with the optical deformation measuring system ARAMIS. The deformation of an applied statistical pattern was observed by two high resolution stereo cameras and local true strain data were calculated. This strain data was used to determine forming limit curves according to ISO 12004.

Standard preparation techniques were applied to take micrographs from the as received sheets and deformed specimens after fracture. The microsections were ground with SiC sandpaper and polished with SiO_2 suspension. Etching agents based on picric acid were used [11]. The observation direction was the transversal direction of the sheet for all specimens.

Results

The as received microstructures of the four sheets are shown in Fig. 1. It is noteworthy that the sheets of two different alloys and two different process routes all show a comparable microstructure of equiaxed grains with a mean grains size of 10-12µm. This means that for the further considerations, effects of the initial grain size can be neglected.

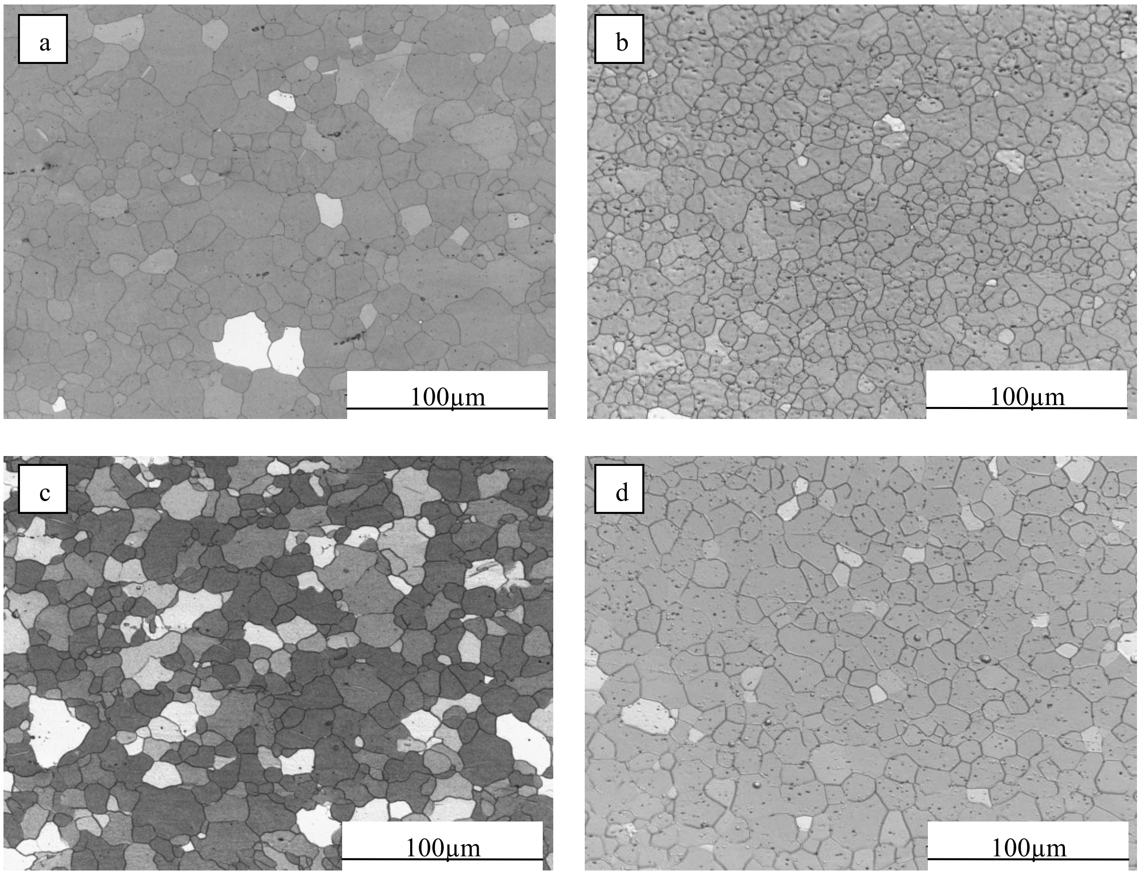

Fig. 1: Microstructure of sheets (a) AZ31 from slab, (b) AZ31 from TRC strip, (c) ZE10 from slab and (d) ZE10 from TRC strip

The textures of the sheets are shown as recalculated (0002) pole figures in Fig. 2. The AZ31 sheets rolled from slab and TRC strip feature a typical basal type texture with the majority of the basal planes being oriented in the sheet plane. This type of texture is a common finding for conventionally rolled magnesium sheets. While the basal pole is approximately symmetric for the sheet rolled from strip, the sheet from slab shows a spread of the basal poles towards the rolling direction. This type of texture is also present for ZE10 sheet rolled from twin roll cast strip. However, the maximum intensity is less for ZE10 than AZ31 from any production route. Rare earth additions are known to reduce the intensity of the textures of wrought magnesium alloys [4,5]. The ZE10 sheet rolled from slab shows a different type of texture with a spread double peak at 45° towards the transversal direction. The maximum intensity is the lowest of all tested sheets. The basal planes as main slip planes are oriented in a more favourable way when loaded in the sheet plane and internal stresses due to localisation of deformation are reduced.

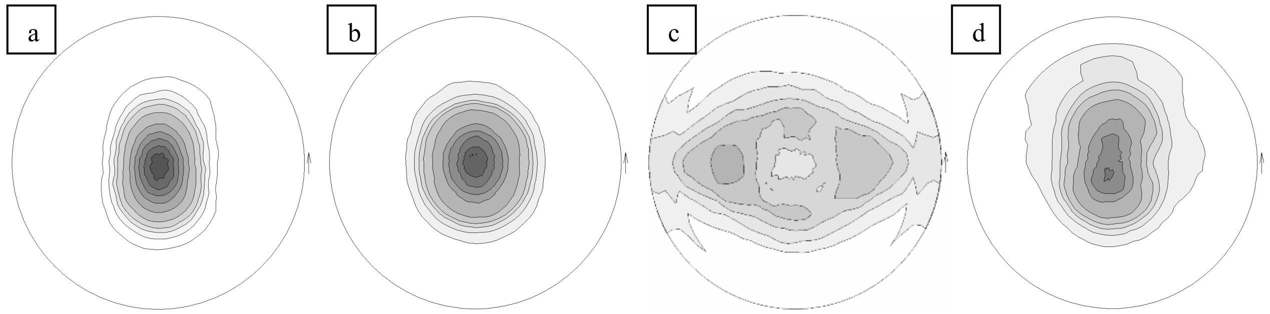

Fig. 2: 0002 pole figures of sheets (a) AZ31 from slab (I_{max} = 14.6 m.r.d.), (b) AZ31 from TRC strip (I_{max} = 13.2 m.r.d.), (c) ZE10 from slab (I_{max} = 3.6 m.r.d.) and (d) ZE10 from TRC strip (I_{max} = 9.2 m.r.d.)

Table 1 summarises the results from quasi-static tensile tests. The orientation dependence of the tensile yield strength (TYS) reveals the anisotropy of the sheets. While for AZ31 rolled from TRC strip the relative difference of the TYS is lowest, the most pronounced yielding anisotropy is found for conventionally rolled ZE10 sheet. As a trend, the TYS of AZ31 sheet is higher than that of ZE10 sheet. The same holds for the ultimate tensile strength (UTS) which does not show a significant anisotropy. While the uniform elongation of all sheets is on a comparable level, the maximum elongation of conventionally rolled ZE10 sheet outperforms the other sheets.

Table 1: Mechanical properties of AZ31 and ZE10 sheets rolled from slabs and TRC strips in the rolling direction (RD) and the transverse direction (TD)

	AZ31 slab		**AZ31 strip**		**ZE10 slab**		**ZE10 strip**	
	RD	**TD**	**RD**	**TD**	**RD**	**TD**	**RD**	**TD**
TYS [MPa]	154	194	186	202	161	104	139	166
UTS [MPa]	259	262	269	271	234	215	220	228
Uniform elongation [%]	15	13	15	14	12	19	15	14
Elongation [%]	22	20	21	16	28	34	16	22

The forming limit curves of the four sheets as evaluated according to ISO 12004 from the measured strain data are shown in Fig. 3. Fig. 3 (a) shows the FLCs of the conventionally rolled AZ31 and ZE10 sheets while Fig. 3 (b) shows the data for AZ31 and ZE10 sheets rolled from TRC strips. The indicated data points represent the onset of necking of each set of Hasek specimens while the line acts as a guideline for the eye.

At room temperature, the formability of the sheets rolled from slabs is low. ZE10 shows slightly better values in achievable major strain for any strain path. It is noteworthy that the maximum major strain for AZ31 is achieved under a strain path with negative minor strain while for ZE10, a strain path with positive minor strain promises best room temperature formability. At 200°C testing temperature, the values of maximum major strain at the onset of necking increase significantly for AZ31 and ZE10 as well. For AZ31, a sharp V-shape of the FLC is found while for ZE10, the minimum of the FLC is much less pronounced. This critical minimum, denoted FLC_0, usually limits the drawability of sheet metal in deep drawing processes. The FLC_0 of ZE10 sheet from slabs at 200°C is with 0.41 highest of all tested sheets. AZ31 shows the highest formability at the outermost left edge of the FLD of all tested sheets.

For the sheets rolled from TRC strips, formability at room temperature turns out to be poor with ZE10 showing slightly better forming potential under biaxial loading. Increasing the testing temperature to 200°C results in a significant increase of formability for both sheets. The highest gain in major strain at the onset of necking is found for the left hand branch of the FLC which represents strain paths with negative minor strain. The forming limit curves of both AZ31 and ZE10 sheet show a typical V-shape with a pronounced minimum in formability under plane strain conditions. Under biaxial loading with positive minor strain, ZE10 clearly outperforms AZ31. This strain path is relevant for forming components by stretch drawing as done in the automotive industry.

In comparison, AZ31 sheet from TRC strips shows slightly lower formability under all conditions. With the exception of the outermost left edge of the FLC, conventional AZ31 sheet from slab also shows inferior formability, especially under plane strain conditions. ZE10 sheets from slab as well as from TRC strips outperform their counterparts of AZ31 in terms of formability, regardless of the production process. However, ZE10 sheet from TRC strips shows the general characteristic of a sharp V-shaped FLC while ZE10 sheet from slab does not show a pronounced minimum of formability under plane strain conditions.

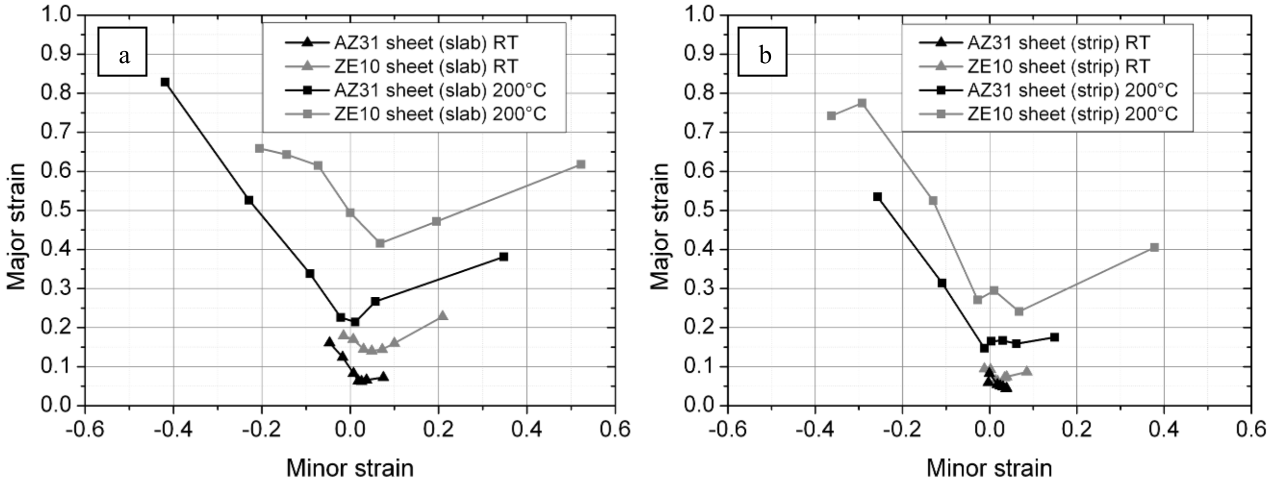

Fig. 3: Forming limit curves of AZ31 and ZE10 sheets (a) rolled from slabs and (b) TRC strips

Micrographs of the microstructure of specimens after fracture are shown in Fig. 4 and Fig. 5. The testing temperature was 200°C and the micrographs show specimens from the outermost left edge of the FLC (negative minor strain) and the right hand edge (positive minor strain). In Fig. 4, the micrographs of specimens rolled from slab are shown. In AZ31, under negative minor strain, continuous bands of very small recrystallised grains are found between large elongated grains. Under positive minor strain, a more homogeneous distribution of the recrystallised grains is found. For ZE10, the microstructure consists mostly of elongated, unrecrystallised grains that form a pan-cake like structure. Elongation of the grains is highest for the specimen with positive minor strain. Only a very small volume fraction of recrystallised grains could be detected at the grain boundaries of the large elongated grain under positive minor strain.

Fig. 5 shows the corresponding micrographs of sheets rolled from TRC strips. Compared to the initial microstructure as shown in Fig. 1, all specimens exhibit a partially recrystallised microstructure of small, newly formed grains and elongated unrecrystallised grains. The fraction of recrystallised volume is higher for ZE10 than for AZ31. Additionally, many precipitates are present in AZ31.

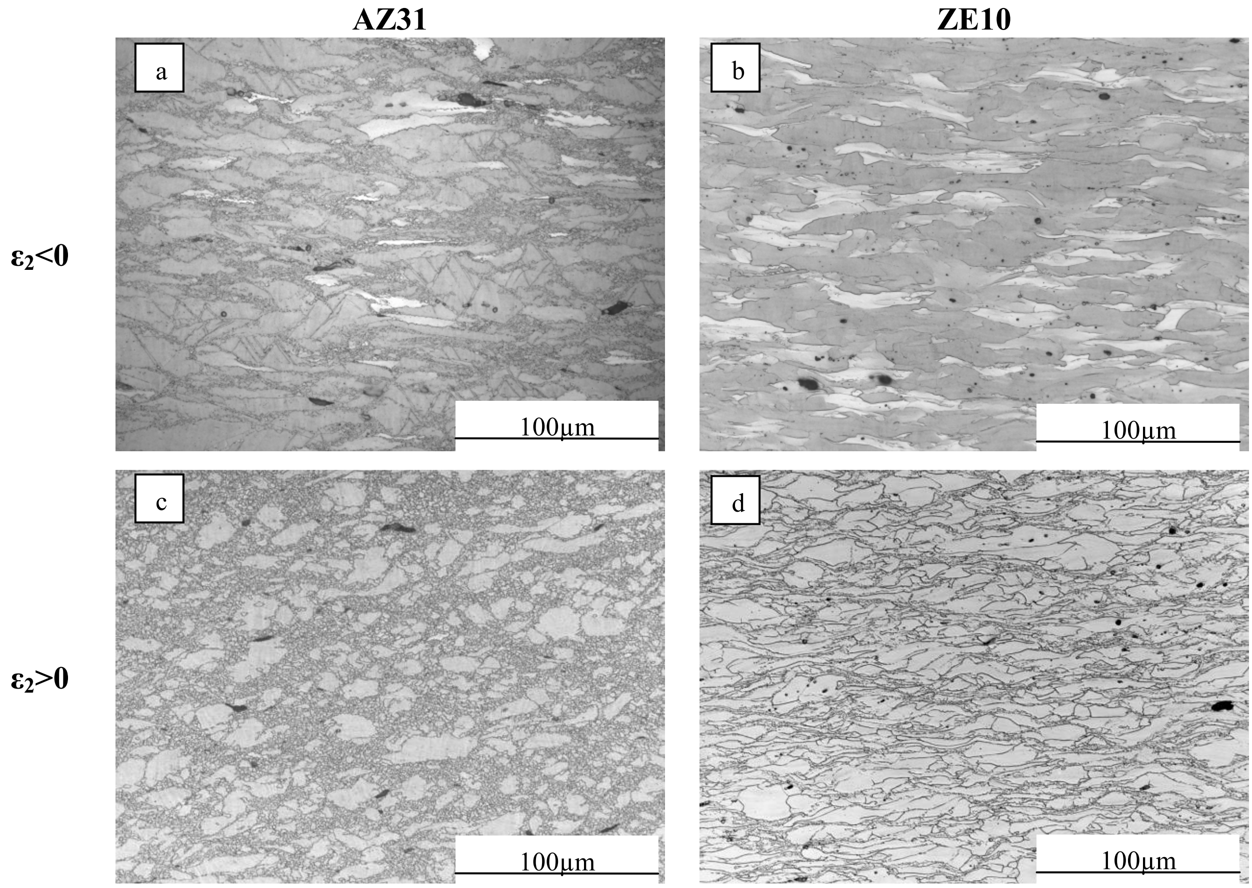

Fig. 4: Micrographs of AZ31 and ZE10 sheets rolled from slabs, tested at 200°C

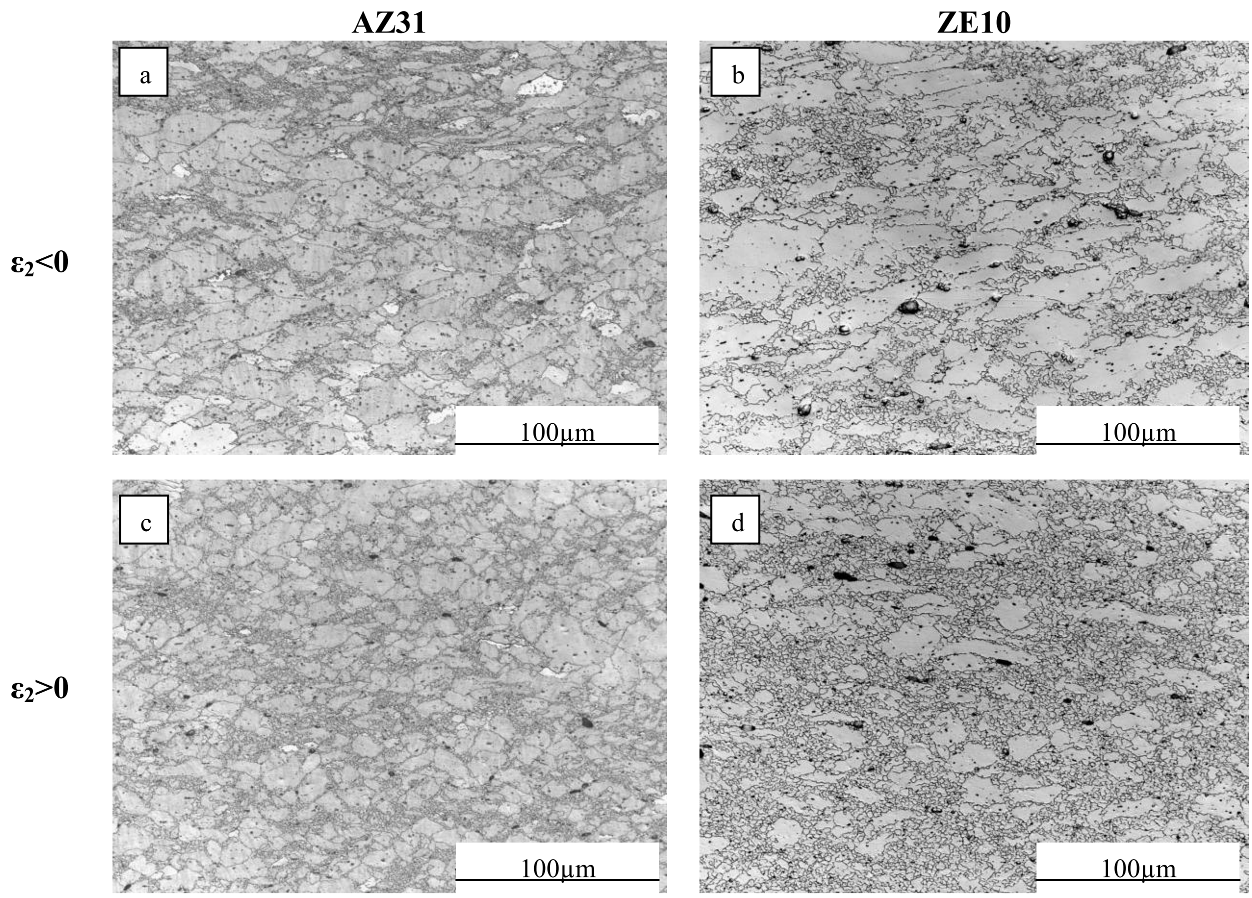

Fig. 5: Micrographs of AZ31 and ZE10 sheets rolled from TRC strips, tested at 200°C

Discussion

The mechanical properties of the sheets can be correlated with the measured textures. The anisotropy of the tensile yield strength is related to the spread of the basal poles. For conventionally rolled AZ31 and ZE10 from TRC strip, there is a distinct spread of the basal poles to the rolling direction. When loaded in this direction, more basal planes are oriented favourably for basal slip, resulting in lower tensile yield stress than for the transverse direction [3]. AZ31 from TRC strips with the lowest yield anisotropy shows the most symmetrical basal texture of all tested sheets. The comparable high maximum elongation of conventionally rolled ZE10 can be related to the weak texture. A more random orientation of basal planes results in a desirable work hardening behaviour which stabilizes the plastic flow of the material [3].

The formability of the four sheets differs as their alloy, production process and resulting texture differs. For magnesium sheets, it is suspected that weakening the texture results in increased formability [3,6,7,8]. Sharp basal type textures hamper deformation in this main slip system due to an unfavourable orientation of the basal planes to the loading axis. Strain perpendicular to the sheet plane is difficult to realise with the majority of basal planes being oriented in the sheet plane. At room temperature, only twinning can contribute to deformation along the <c> axis of the hcp crystal. This results in overall low formability at room temperature of the tested sheets. At elevated temperatures such as 200°C, pyramidal <c+a> slip can accommodate deformation along the <c> axis and thus, formability increases with increasing temperature significantly. It is noteworthy that from the sheets with basal type texture – the AZ31 sheets and the ZE10 sheet rolled from TRC strips – the highest overall formability can be achieved with the sheet with the weakest texture, namely ZE10 from TRC strips. This sheet outperforms conventionally rolled AZ31 which can be regarded a benchmark material as the most common magnesium sheet alloy. A weak texture results in more basal planes being oriented favourably for basal slip and the material has a higher work hardening potential before localisation of deformation happens. Thus, the sheet with the weakest texture, ZE10 rolled from slabs, exhibits the highest overall formability and especially the highest FLC_0. The activation of deformation mechanisms is directly related to the texture of the material, as concluded by Bohlen et al. for uni-axial tension [3].

Depending on the texture, also a change in the dynamic recrystallisation behaviour of the sheets can be observed. While at 200°C testing temperature all tested sheets with a basal type texture form a partially recrystallised microstructure, ZE10 sheet rolled from slabs shows only little evidence of dynamic recrystallisation despite a high degree of deformation. It is known from earlier studies that an addition of rare earth elements to magnesium retards recrystallisation during rolling of magnesium sheets [4]. Although this result holds for binary magnesium alloys, very similar results are obtained for more complex alloys, such as ZE10. Based on this it is assumed that the same retardation plays a role during forming of the sheets. Thus, a comparison of AZ31 and ZE10 must also take into account the different kinetics of recrystallisation. However, comparing the two ZE10 sheets rolled from different precursors the influence of the texture of the sheet becomes obvious if a slight difference in the alloy composition (the Zr content) is neglected. Then it can be concluded that the sheet with the stronger texture leads to earlier dynamic recrystallisation.

Summary and Conclusions

The present study confirms the influence of texture on the deformation behaviour and the formability of magnesium sheets. Four sheets of two alloys with two different processing histories were tested. Sheets rolled from twin roll cast strips are compared to conventionally rolled counterparts. The rare earth element containing alloy ZE10 shows superior formability compared to the alloy AZ31 when comparing the same process routes. The main reason for this is the weaker texture of the rare earth element containing alloy ZE10. The sheets from TRC strips in this study already outperform conventional AZ31 sheets. By further optimisation of the TRC process, tailoring the texture of magnesium sheets can achieve the goal of good formability at moderate processing temperatures.

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