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Cold Formability of Twin-Roll Cast, Rolled and Annealed Mg Strips

Madlen Ullmann *, Kristina Kittner and Ulrich Prahl

Institute of Metal Forming, Technische Universität Bergakademie Freiberg, Bernhard-von-Cotta-Str. 4, 09599 Freiberg, Germany; kristina.kittner@imf.tu-freiberg.de (K.K.); ulrich.prahl@imf.tu-freiberg.de (U.P.)
* Correspondence: madlen.ullmann@imf.tu-freiberg.de

Abstract: This study investigates the cold formability of twin-roll cast and rolled magnesium strips, specifically focusing on AZ31 and ZAX210 alloys. The aim is to assess the suitability of these alloys for various forming processes. The mechanical properties and formability characteristics of the strips were thoroughly examined to provide insights into their potential applications in transportation industries such as automotive and aerospace. The AZ31 and ZAX210 alloys were subjected to twin-roll casting and rolling processes to produce thin strips. The resulting strips were then evaluated for their cold formability. The results indicate that both alloys exhibit favourable cold formability. The ZAX210 alloy, in particular, demonstrates medium strengths with an average tensile strength of approximately 240 MPa at room temperature. The 0.2% proof stress values range between 136 MPa and 159 MPa, depending on the sampling direction. The total elongation values vary from 28% in the transverse direction to 32% at a 45° angle, indicating excellent ductility. Comparing the two alloys, the AZ31 alloy shows higher strengths due to its higher aluminium content. However, it also exhibits a more pronounced directional dependence of mechanical properties due to the formation of a strong basal texture during hot rolling. The transverse direction experiences reduced total elongation compared to the rolling direction, achieving only about 50% of the total elongation. The average Erichsen Index recorded for AZ31 and ZAX210 strips were 4.9 mm and 7.1 mm, respectively. The ZAX210 strip displays superior formability, which can be attributed to the fine-grained microstructure and the texture softening resulting from the weakening of the basal texture intensity and the splitting of the basal pole towards the rolling direction. In conclusion, the investigated twin-roll cast, rolled and annealed AZ31 and ZAX210 magnesium strips exhibit promising cold formability characteristics. The findings of this study contribute to the understanding of their mechanical behaviour and can guide the selection and optimisation of these alloys for various forming applications.

Keywords: magnesium alloys; cold formability; twin-roll casting; rolling; Mg-Zn-Al-Ca; Erichsen Index; mechanical properties; FLC

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1. Introduction

Magnesium alloys have gained significant attention in various industries due to their low density, excellent mechanical properties, and high specific strength. However, the inherent poor formability of magnesium alloys at room temperature (RT) poses challenges in their practical applications, particularly in cold forming processes. Sheet metal forming processes like deep drawing, cupping operations or bending operations require elevated temperatures when magnesium alloys are used. To decrease forming temperatures, different factors must be considered. The cold formability of magnesium alloys is influenced by several factors, including alloy composition, microstructure, texture, processing methods and the manufacturing process itself. Among these factors, alloy composition plays a crucial role in determining the formability characteristics [1,2].

The low formability of magnesium alloys at room temperature is mainly attributed to the hexagonal lattice and the strongly pronounced basal texture during conventional wrought processing. This is accompanied by a stronger anisotropy and lower stretch formability. In order to overcome these disadvantages, several studies have focused on increasing room temperature formability by adding alloying elements and developing appropriate processing technologies in order to attain texture weakening resulting in an advantageous effect on the plasticity of wrought magnesium alloys at room temperature [1]. Alloying elements that contribute to the development of weak textures are rare earths elements (REs) and calcium [3–6]. Rare earths elements are disadvantageous due to their rarity, high costs and difficulties in mining, despite their positive property effects. New developed magnesium alloy systems with low RE-content or Ca addition offering a high RT stretch formability include (among others) Mg-Zn-RE, Mg-Sn-RE, Mg-Zn-Ca and Mg-Al-Ca-Mn systems [1,7]. These alloys exhibit an excellent RT formability with a high Index Erichsen (IE) value of between 7 mm and 9 mm. However, increased RT formability is accompanied by lower strength values due to the strength–ductility trade-off dilemma [8]. Magnesium alloys exhibiting higher strength, for example Mg-Mn- or Mg-Al-based alloys, offer inferior formability, with IE values between 3 mm and 5 mm. In turn, the alloying elements RE and Ca have a favourable effect, as they enable an increase in strength through age- or bake-hardening treatments while at the same time exhibiting the respective weak textures [9]. Table 1 shows a summary of the mechanical properties and stretch formability (IE) of several magnesium alloys.

Table 1. Summary of mechanical properties and Index Erichsen (IE) values of typical Mg alloy sheets compared to Al AA6xxx alloy sheet at RT (along the rolling direction; TYS: tensile yield strength, TE: total elongation).

Alloys (Wt%)	Processing Condition	TYS (MPa)	TE (%)	IE (mm)	References
AZ31	Hot rolling, annealing	166	23	2.6	[10]
AZ61	Extrusion, hot rolling, annealing	152	24	7.8	[11]
AZ80	Extrusion, hot rolling, annealing	187	24	3.7	[12]
Mg-3Al-1Zn-1Mn-0.5Ca	Twin-roll casting, hot rolling, annealing	219	16	8.0	[13]
AZ31	Hot rolling, annealing	179	22	3.4	[14]
WE43	Hot rolling, annealing	228	15	1.7	[15]
Mg-4.6Zn-0.6Ce-0.3La-0.2Nd	Hot rolling, T4	128	12	3.7	[16]
Mg-4.0Zn-0.3Y-0.3Ca	Twin-roll casting, hot rolling, annealing	176	26	7.6	[17]
AA6xxx	T4, naturally aged	180	27	9.1	[18]

Bian et al. (2020) [8] investigated the influence of different Ag contents on the mechanical–technological property profile of Mg-xAg-0.1Ca (0.3 ... 12 wt% Ag) alloys after extrusion and hot rolling. With the addition of 6 wt% Ag, the maximum values of IE 8.7 mm and yield strengths between 138 MPa (TD) and 182 MPa (RD) are achieved. The good formability at RT is attributed to the fine-grained microstructure accompanied by a weak TD-split texture, and the high strength to the dense distribution of fine AgMg4 particles. Jo et al. (2022) [9] showed an increased IE of 6.3 mm and yield strength values of 150 MPa after peak ageing of a ZAXM2100 magnesium alloy. The authors attribute the improved properties to a weakened texture with a basal pole split towards the RD and a broad angular distribution towards the TD as well as a fine-grained microstructure, which developed as a result of grain boundary pinning by Al2Ca. Weakened textures as a basis for the improved room temperature formability of several magnesium alloys are also reported by other research groups, for example, for AZ31 [19,20], ZMX21 [21] and

AZX612 [2]. Besides adding alloying elements, as mentioned above, appropriate processing technologies are also suitable for texture weakening. Han et al. 2023 [22] reported on the double-peak texture of AZ31 introduced to equal channel angular rolling combined with continuous bending and annealing, resulting in superior cold rolling formability.

Wang et al. (2021) [1] summarised in their review that RE- and Ca-containing magnesium alloys, which are subjected to extrusion or rolling–annealing procedures, reveal weak off-basal textures and homogeneous fine-grained microstructures. Microstructure and texture development are attributed to dynamic and static recrystallisation mechanisms associated with the change in the stacking fault energy and the activity of non-basal slip systems [1,13,17,23–25].

In the present work, tensile tests, and Erichsen tests are performed on and forming limit diagrams are created for the magnesium alloys AZ31 (Mg-3Al-1Zn) and ZAX210 (Mg-2Zn-1Al-0.3Ca), which were produced by the innovative twin-roll casting process and a following rolling process, to compare the effects of the different Mg alloys on the tensile properties and formability at room temperature. The insights gained from these investigations can contribute to the development of magnesium alloys with improved formability and enable their wider adoption in industries such as automotive, aerospace, and consumer electronics. The present work shows that sheet metal forming processes at low temperatures are possible with the ZAX210 alloy. In addition, a process whose industrial realisation has already been demonstrated is used via the production route of twin-roll casting combined with hot rolling. This means that the improved property profile is not just limited to laboratory-scale investigations.

2. Materials and Methods

2.1. Material

For the present investigations, magnesium sheets of the Mg-2Zn-1Al-0.3Ca (ZAX210) and Mg-3Al-1Zn (AZ31) alloys were employed. These sheets were produced through a combination of twin-roll casting and rolling processes, and a final annealing process. Twin-roll cast coils have a width of 730 mm. After trimming and hot rolling the final width of the coils was 650 mm. The resulting sheets had a uniform thickness of 1.5 mm. The chemical composition of the ZAX210 and the AZ31 strips, measured by means of radio spectral analysis, is provided in Table 2.

Table 2. Nominal chemical composition of ZAX210 and AZ31 alloys under investigation (wt.-%).

Alloy	Mg	Zn	Al	Ca	Mn	Cu	Fe	Ni	Si	Others
ZAX210	Bal.	2.29	0.92	<0.24	0.04	0.001	0.005	0.001	0.022	<0.020
AZ31	Bal.	0.85	2.92	0	0.32	0.001	0.005	0.001	0.021	<0.004

2.2. Experimental Procedure

The cast ingots were used as the initial material for the twin-roll casting process. The pilot plant for TRC at the Institute of Metal Forming, TU Bergakademie Freiberg, consists of a melting furnace, a casting channel and a casting nozzle. The twin-roll casting process was conducted at temperatures between 690 °C and 710 °C with casting speeds of 1.4 m/min. Further information can be found in [26]. The entire process takes place in an inert gas atmosphere.

The twin-roll cast sheets were homogenised at 430 °C (AZ31) or 380 °C (ZAX210) for 6 h. The hot rolling of the TRC sheets was performed in four passes from an initial thickness of 5.2 mm to a final thickness of 1.5 mm with an intermediate annealing stage at 430 °C (AZ31) or 380 °C (ZAX210) for 2 h. The four passes were from 5.2 mm to 3.6 mm to 2.7 mm and from 2.7 mm to 2 mm to 1.5 mm with a rolling speed of 100 m/min on a reverse rolling mill located in the Institute of Metal Forming at Technische Universität Bergakademie Freiberg, Germany. The rolling schedule was set with a strain of 0.28 and 0.37 in order to induce dynamic recrystallisation during hot rolling. After hot rolling, a final annealing was performed at 330 °C for 1 h. Samples for microstructural and texture characterisation were cut from the TRC, homogenised, hot rolled and finally annealed sheets. The choice of rolling and annealing parameters was based on [27] for AZ31 and [26] for ZAX210.

2.3. Material Characterisation

Samples for microstructure and texture analysis were metallographically prepared by grinding and polishing. Etching was carried out using a picric acid solution consisting of 70 mL of ethanol, 10 mL of distilled water, 10 mL of glacial acetic acid and 4.2 g of picric acid. Light microscopic images were taken using a Keyence VHX 6000 microscope at the Institute of Metal Forming, Freiberg, Germany. A scanning electron microscopic (SEM) evaluation was performed using a ZEISS GeminiSEM 450 device at the Institute of Metal Forming, Freiberg, Germany. Different detectors were used for SEM: angular selective backscatter (AsB), backscatter (BSE) and secondary electron detector (SE). Texture analysis was performed using an electron backscatter diffraction detector (EBSD). The accelerating voltage was between 15 and 20 kV. A step size of 0.65 µm was selected. The free MTEX MATLAB toolbox (version 5.8.1, MTEX, [28]) was used for the analysis of the EBSD data and the calculation of the pole figures. A microstructural analysis was carried out on longitudinal sections.

Tensile tests were performed to determine the tensile strength and total elongation of the materials according to DIN EN ISO 6892-1 [29]. Sample dimensions correspond to flat tensile samples, shape H, according to DIN 50125 [30]. The tests were carried out at room temperature, and the samples were loaded in the 0°, 45° and 90° directions with respect to the rolling direction. Five parallel tests were carried out in each case. An extensometer was used to measure the strain of a specimen under load. The results from the tensile tests provided valuable insights into the strength and ductility of the alloys.

To assess the stretch formability, Erichsen tests were conducted on the twin-roll cast, rolled and annealed strips according to DIN EN ISO 20482 [31]. The Erichsen test measures the ability of a sheet material to withstand plastic deformation without cracking or fracture. The average values of the Erichsen cup heights were recorded for both AZ31 and ZAX210 strips, providing quantitative data on their formability characteristics. By comparing the results, the relative formability of the alloys can be determined.

Furthermore, forming limit curves (FLCs) were created according to ISO 12004-2 [32] to analyse the formability of the alloys under different strain conditions. The Nakajima test, a widely used method for FLC determination, was employed. The test involves deforming specimens with varying notch widths using a hemispherical punch. A 1.00 ± 0.02 mm square grid was applied on the specimen surface via transfer printing for strain measurement which was conducted in situ with four cameras through the strain measuring system AutoGrid (ViALUX). The strains at which necking or fracture occurred provide crucial information about the formability limits of the materials. The FLCs obtained from the Nakajima tests allow for a comprehensive understanding of the sheet metal forming behaviour, considering the effects of stress condition, of both alloys.

3. Results

Characterisation of the Initial AZ31 and ZAX210 Strips

The inverse pole figure (IPF) maps, equivalent grain sizes and the backscattered electron images (BSE) of the twin-roll cast, rolled and annealed strips of AZ31 and ZAX210 are shown in Figures 1 and 2, respectively. Both alloys show approximately the same grain size: AZ31 has an average value of 7.9 µm, and ZAX210 has an average value of 8.9 µm. The AZ31 strips reveal finely distributed Al_8Mn_5 particles in α-Mg. The $Mg_{17}(Al,Zn)_{12}$ phases are dissolved according to [7]. The ZAX210 strips show Mg_2Ca-, MgZn- and $Ca_2Mg_6Zn_3$-phases in α-Mg, based on [33].

(**a**) (**b**) (**c**)

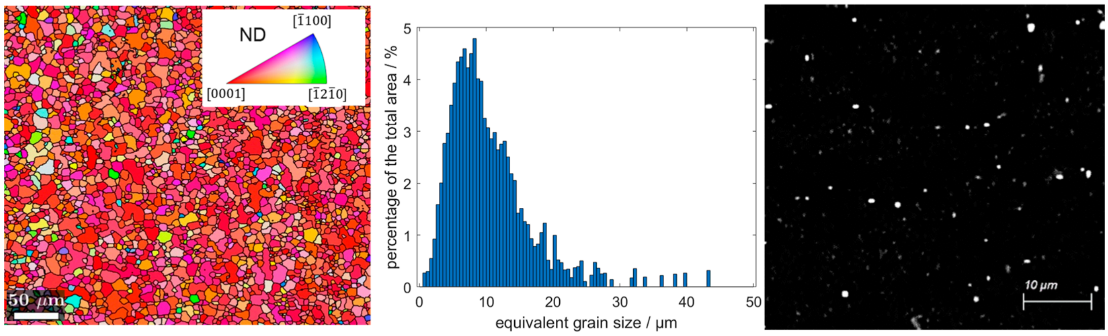


Figure 1. (**a**) Inverse pole figure (IPF) maps from longitudinal sections (TRC and rolling direction horizontal) of the twin-roll cast, rolled and annealed AZ31 strips, (**b**) equivalent grain sizes and (**c**) SE contrast.

(**a**) (**b**) (**c**)

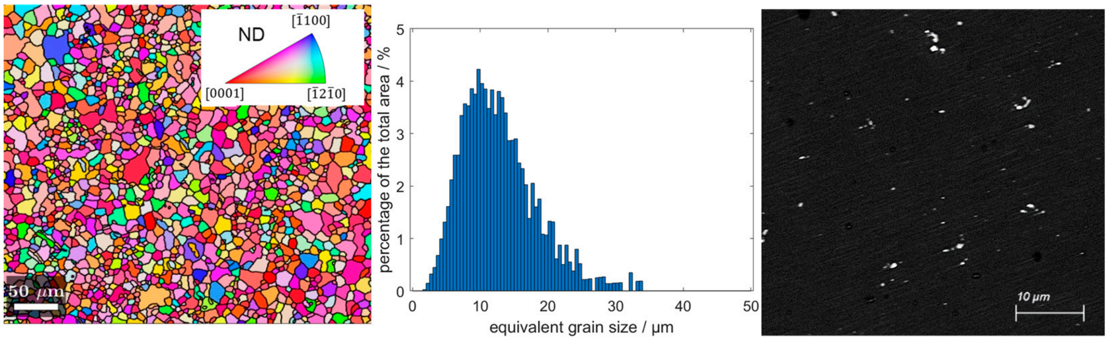


Figure 2. (**a**) Inverse pole figure (IPF) maps from longitudinal sections (TRC and rolling direction horizontal) of the twin-roll cast, rolled and annealed ZAX210 strips, (**b**) equivalent grain sizes and (**c**) SE contrast.

The influence of the alloying elements on the texture can be clearly seen in the IPFs and pole figures (Figure 3). Ca effectively weakens the intensity of the basal texture. AZ31 shows a strong and pronounced $\langle 0001 \rangle$ fibre parallel to the normal direction (ND) and a maximum intensity of and MRD of 10. Prismatic planes are randomly distributed parallel to the ND and weakly pronounced with 2.8 MRD. This texture is typical for rolled or extruded AZ31 strips [1,26]. The texture of ZAX210 differs significantly from that of AZ31. The basal pole figure (Figure 3b) shows the well-known split of the centre pole into two poles that tilt from the ND towards the RD. Ca can lead to this texture formation. Bian et al. (2020) [8] reported on RD split textures with double peaks after the hot rolling of a Ca-containing Mg-Ag magnesium alloy. Further studies also present weakened textures after the hot deformation of magnesium alloys after Ca addition [1,2,34]. Additionally, the maximum basal pole intensity is only 2.5 MRD. The prismatic planes show a weak preferred alignment in the TD with a maximum pole density of 1.7 MRD.

The mechanical properties of the twin-roll cast, rolled and annealed strips are shown in Table 3. The ultimate tensile strength (UTS) is not strongly influenced by a 0°, 45° or 90° direction. Only for the AZ31 alloy, there are some slightly higher values in 0° direction than in 90°.

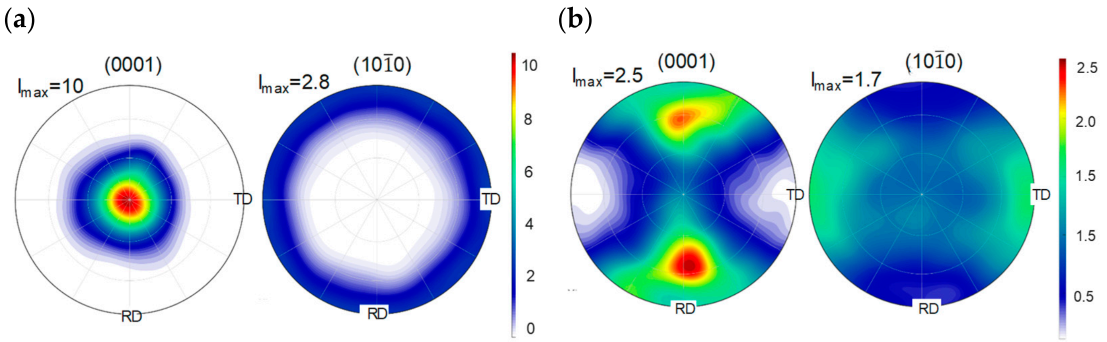
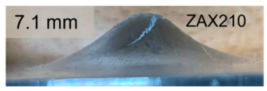


Figure 3. Pole figures of the twin-roll cast, rolled and annealed Mg strips. (**a**) AZ31, (**b**) ZAX210 (intensities in multiples of random distribution—MRD).

Table 3. Mechanical properties and IE of the twin-roll cast, rolled and annealed Mg strips.

Strips	Direction	TYS (MPa)	UTS (MPa)	TE (%)	UTS/YS	I.E.	
AZ31	RD	198 ± 5	280 ± 6	24 ± 2	1.4		
	45°	195 ± 6	276 ± 6	22 ± 2	1.4	4.9 ± 0.2	
	TD	189 ± 5	273 ± 5	18 ± 1	1.4		
ZAX210	RD	159 ± 3	248 ± 4	30 ± 2	1.6		
	45°	145 ± 3	238 ± 3	32 ± 2	1.6	7.1 ± 0.3	
	TD	136 ± 3	242 ± 4	28 ± 3	1.8		

The lowest total elongation (TE) was found at 90°, and the largest one was found at 0° for both alloys, in which the difference in AZ31 strips is much higher than that in the ZAX210 strips.

At room temperature, the ZAX210 alloy exhibits medium strengths with tensile strengths of about 240 MPa. The 0.2% proof stress (TYS) varies between 136 MPa (TD, 90°) and 159 MPa (RD, 0°) depending on the sampling direction. The Excellent total elongation of 28% (TD, 90°) to 32% (45°) are achieved. The deviation between the mechanical properties in and transverse to the rolling direction is a maximum of 15%. A comparison with AZ31 shows higher strengths than ZAX210 due to the high aluminium content. However, the directional dependence of the mechanical properties is more pronounced, due to the strong basal texture formed during hot rolling. For example, transverse to the rolling direction, only about 50% of the total elongation can be achieved in the rolling direction.

In comparison with the literature on rare-earth-containing magnesium alloy ZE10, which exhibits a weak basal texture with intensity maxima along the rolling direction, pole broadening in the transverse direction in the rolling direction and finally annealed state shows that similar mechanical properties are achieved for ZAX210. Due to the basal pole broadening in TD for ZE10, higher total elongations in the 90°-direction are achieved [26]. These results are in agreement with the literature [1,24].

To investigate the impact on stretch formability at room temperature, Erichsen tests were performed on both alloys. An average Erichsen Index (I.E.) of 4.9 mm and 7.1 mm were recorded for twin-roll cast, rolled and annealed AZ31 and ZAX210 strips, respectively. The significant high formability of the ZAX210 strip is closely related to the texture softening originating from the weakening of basal texture intensity and the splitting of the basal pole towards the RD. Generally, the stretch formability is mainly dependent on the microstructure and texture of the sheets and the associated forming mechanisms. Particle-stimulated nucleation (PSN), recrystallisation at deformation and shear bands, changes in grain boundary mobility brought on by secondary phases, and recrystallisation at double and compression twins are possible mechanisms for the weakening of textures [1,2,8,21].

As written in Kittner et al. (2022) [33] recrystallisation due to PSN can be excluded in the current ZAX210 strip. Rather, this strongly weakened texture, in which the c-axis of the crystallites is tilted from the normal direction (ND) to the RD-direction primarily, is caused by continuous or twin-induced dynamic recrystallisation at double and compression twins. Additionally, it is possible that Ca, which segregates at grain boundaries, limits their mobility. As a result, the intensity of the resulting texture is affected, and the preferential growth of grains is inhibited [33]. In Wang et al. (2021) [1], the weak off-basal texture after extrusion or rolling-annealing procedures is attributed to a homogeneous fine-grained microstructure as a result of dynamic and/or static recrystallisation associated with the activity of the non-basal slip systems and the chance of stacking fault energy.

Figure 4 plots the Erichsen Index and tensile yield strength values of AZ31 and ZAX210 of this study at room temperature compared to other magnesium alloys from the literature as well as the AA6xxx aluminium alloy sheet. Compared to the commercial AZ31, AZ80 and WE43 alloys, the twin-roll cast, hot rolled and finally annealed AZ31 and ZAX210 alloys show improved room temperature formability with comparable tensile yield strength (except in relation to WE43). Compared to other newly developed magnesium alloys with Ca addition, the ZAX210 alloy exhibits a slightly lower room temperature formability but has excellent elongation at fracture. The outstanding combination of strength, ductility and formability of the ZAX210 magnesium alloy, which is comparable to those of AA6xxx aluminium alloy sheets, leads to an increased potential of those magnesium alloys for a wide range of applications, especially in the field of room-temperature forming.

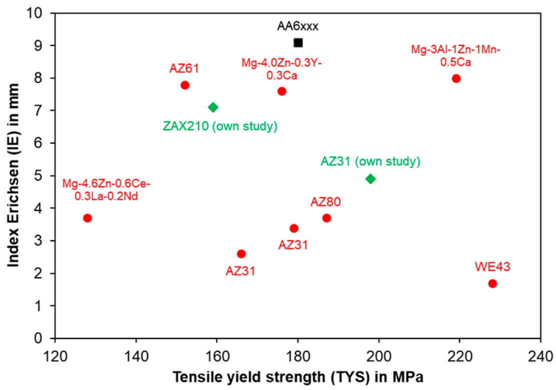


Figure 4. Index Erichsen (IE) values versus tensile yield strength (TYS) of various magnesium alloys (red) from the literature (according to Table 1) compared to an aluminium alloy (black) as well as AZ31 and ZAX210 from this study (green), adapted from [10–18].

For the further analysis of cold forming, forming limit strains are determined at room temperature using the Nakajima test. It is important to note that the forming operation along with the left side of the FLC are based on the strain condition that allows the material to contract along the minor strain axis but with little to no reduction in thickness. In contrast, on the right side of the wide FLC, the forming operation requires a positive strain in all the sheet plane directions, and the material flow is realised by thinning the sheet. The overall minimum depends on the plane strain condition in V-shaped curves. Such a result can be seen for the ZAX210 and AZ31 sheets in Figure 5. As expected, the forming limit value for ZAX210 sheet is higher than for AZ31 sheet. Compared to the above forming operation, the ZAX210 strains on the left side of the FLC are higher than those on the right side. For forming operations with a deep-drawing component as well as uniaxial tension, higher forming changes are therefore possible at room temperature. In the range of negative minor strain, the major strain is φ_1 = 0.35. The stretch-forming capacity and the forming capacity in the plane strain state are at a comparable level with φ_1 = 0.2.

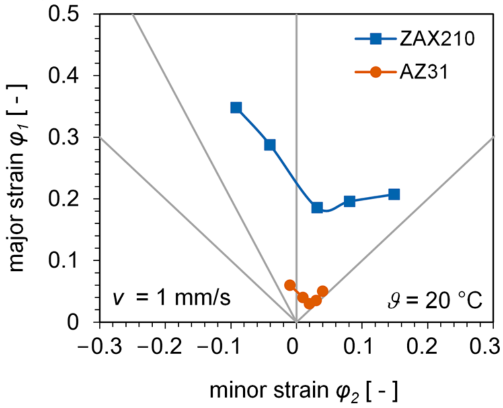


Figure 5. Forming limit curves of the twin-roll cast, rolled and annealed ZAX210 and AZ31 strips at room temperature.

In comparison with the literature values, the ZAX210 finished strip exhibits a comparable, partly higher forming capacity than strips of a ZE10 alloy [35]. Due to their chemical composition—ZE10 as a result of the addition of rare earth elements and ZAX210 as a result of the addition of Ca—both alloys have weakened textures after rolling, which are generally accompanied by improved formability.

4. Conclusions

The investigation focused on the characterisation of twin-roll cast, hot rolled and finally annealed magnesium sheets of the ZAX210 (Mg-2Zn-1Al-0.3Ca) alloy and its comparison with the AZ31 (Mg-3Al-1Zn) alloy.

i. Both alloys exhibited similar grain sizes, with AZ31 having an average value of 7.9 µm and ZAX210 having an average value of 8.9 µm. The microstructure of the AZ31 strips showed finely distributed Al_8Mn_5 particles in α-Mg, while the ZAX210 strips exhibited Mg_2Ca, MgZn, and $Ca_2Mg_6Zn_3$ phases in α-Mg.
ii. The influence of alloying elements on texture was evident in the IPFs and pole figures. The presence of calcium effectively weakened the intensity of the basal texture in ZAX210, whereas AZ31 exhibited a strong basal texture with a pronounced ⟨0001⟩ fibre parallel to the normal direction (ND). The mechanical properties, including tensile strength and total elongation, were evaluated for both alloys. ZAX210 demonstrated medium strengths with tensile strengths of about 240 MPa and excellent total elongation ranging from 28% to 32%, depending on the sampling direction. A comparison with AZ31 revealed higher strengths in AZ31 due to its higher aluminium content, but also a stronger directional dependence in mechanical properties attributed to its strong basal texture formed during hot rolling.
iii. The formability at room temperature of the alloys was assessed through Erichsen tests, with ZAX210 strips demonstrating significantly higher formability compared to AZ31. The texture softening in ZAX210, resulting from the weakening of basal texture intensity and the splitting of basal poles towards the rolling direction (RD), contributed to its enhanced formability. Recrystallisation at double and compression twins, along with the potential grain boundary segregation of calcium, were identified as mechanisms for the weakened texture in ZAX210 [33]. The ZAX210 alloy offers an outstanding combination of strength, ductility and formability, which is comparable to those of AA6xxx aluminium alloy sheets.
iv. Forming limit strains were determined using the Nakajima test, indicating that ZAX210 exhibited higher forming limit values compared to AZ31. The ZAX210 strip demonstrated higher forming changes on the left side of the forming limit curve (FLC), allowing for deeper forming operations at room temperature. The

forming capacity of ZAX210 is comparable to a ZE10 alloy, which contains rare earth elements, due to the weakened textures achieved after rolling.

In summary, the study revealed that the ZAX210 alloy, with the addition of calcium, exhibited favourable mechanical properties, enhanced formability, and weakened textures, making it a promising material for cold forming applications. In direct comparison to the well-established AZ31 alloy, this new alloy shows much improved formability what will make it a high-potential candidate for future cold forming operations. However, despite the mentioned advances of the ZAX210 magnesium alloy, further research in the field of a simultaneous enhancement in strength, ductility and stretch formability at room temperature is still required. Age or bake hardening procedures are planned for the twin-roll cast, hot rolled and annealed ZAX210 sheets with the aim to increase strength by precipitation hardening.

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Conflicts of Interest: The authors declare no conflict of interest.

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