Original

Kainer, K.U.; Hoppe, R.; Bohlen, J.; Kurz, G.; Yi, S.; Letzig, D.:
**Challenges and Solutions in the Development of Magnesium Sheet
for Sustainable Vehicle Concepts**
Materials Science Forum, Light Metals Technology 2015 (2015)
Trans Tech Publications

DOI: [10.4028/www.scientific.net/MSF.828-829.15](https://doi.org/10.4028/www.scientific.net/MSF.828-829.15)

Challenges and Solutions in the Development of Magnesium Sheet for Sustainable Vehicle Concepts

KAINER Karl Ulrich^{a*}, HOPPE Roland^b, BOHLEN Jan^c, KURZ Gerrit^d,
YI Sangbong^e and LETZIG Dietmar^f

Helmholtz-Zentrum Geesthacht, Magnesium Innovation Centre (MagIC), May-Planck-Str.1,
D-21522 Geesthacht, Germany

^akarl.kainer@hzg.de ^broland.hoppe@hzg.de, ^cjan.bohlen@hzg.de, ^dgerrit.kurz@hzg.de,
^esangbong.yi@hzg.de, ^fdietmar.letzig@hzg.de

Keywords: Magnesium sheets, twin roll casting, texture.

Abstract. Magnesium as the lightest structural metal offers significant potential weight saving compared with steel and aluminium. Cast magnesium components are widely used, e.g. as engine blocks or gear box housings. To open more opportunities for weight saving, it is necessary to widen the application fields to wrought products, such as large thin walled components for which sheets as semi-finished products are needed. The production and processing of magnesium sheet material is currently hampered by the limited formability of magnesium and high costs. The use of the twin-roll casting (TRC) as a cost-effective manufacturing process and the development of new calcium-containing alloys are leading to a decisive reduction of those obstacles.

Introduction

The interest of light-weight applications in metallic construction environments leads focus on magnesium alloys for transportation applications. Magnesium alloys are used successfully in the form of cast components, e.g. Mg wheels, gear housing. Further expansion of Mg in transport applications requires the utilization of products based on wrought processes such as magnesium sheets as semi-finished products for forming large thin-walled components and structures. In making use of the low density of magnesium alloys, competitive development of Mg sheet alloys may be visualized by considering the weight-saving approaches used by other metallic construction materials such as steels and aluminium alloys. The overall performance of magnesium as a metallic material is seen to be advantageous in terms of production, operation and recycling in comparison with non-metallic applications, such as reinforced polymers. The production of formed parts is based on the standardized sheets, a semi-finished product. Every important metal is available in the form of sheets. The generalized production method for sheet material is the rolling process, which uses cast billets as a feedstock material and rolls these into thin sheets or plates following a large scale deformation schedule. The material is deformed between rolls with lower roll gap compared with the cast slab thickness in a number of passes in order to achieve a flat product with homogeneous thickness. This semi-finished product is then available for subsequent processing along the requirements of the potential applications. Therefore, sheet material is of importance if the full potential of magnesium alloys (not only necessarily light-weight construction) is to be realized. In developing the potential light-weight magnesium alloys some drawbacks have to be considered. Magnesium has a hexagonal close packed lattice structure which is seen as an obstacle for high ductility and formability, the properties essential for sheet products. The reason is the limitation of the number of active deformation mechanisms, especially when compared with cubic metals. The fabrication of magnesium sheets has been shown to be feasible some decades ago but the processing routes are complex and therefore expensive limiting the use of sheet magnesium today. The competition between the potential for weight-saving and performance on one side and the specific needs for production routes on the other hand needs to be balanced for the development of

magnesium sheet material. The further development of magnesium for sheet metal production must therefore aim for a randomized texture leading to better formability and to find suitable processes for the production and processing of alloys developed for such applications. Twin roll casting shows strong potential as an economically viable process for the development of magnesium sheet products for mass-production scale. Examples of serial part are shown in Fig. 1.

Fig. 1. Examples of magnesium sheet metal components (a) Rear sheet for the Renault-Samsung SM7 (serial part) [1] and (b) Porsche uses POSCO's mass produced magnesium sheets in the roof of the new model [2].

Processing

Although, the feasibility of sheet production has been shown for a wider selection of magnesium alloys [3, 4], the processing remains complex, time consuming and expensive. Even at high temperatures, this leads to complex rolling plans with a high number of rolling passes at comparably low degree of deformation per pass. It has therefore been recognized that the processing route for magnesium sheets requires an improvement of the efficiency for the production of sheets.

Twin-roll casting of magnesium alloys is seen as a promising processing route to enable a further development of sheet properties. The reduction in the number of processing steps to final gauge, Fig. 2, leads to shorter production times and a decrease in production costs. In this process, liquid metal is pumped from a furnace or oven into a tundish using protective gas to avoid burning. The melt then flows into a flat pipe (tip), leading it into the roll gap of a pair of counter rotating rolls. The metal solidifies upon contact with the rolls and then rolled into a strip with a typical thickness of a few millimetres. The processing parameters in twin roll casting have a significant influence on the microstructure and texture of the strips. For example, by varying the position of the solidification front will influence the microstructure of the strip, Fig. 2.

Fig. 2. Comparison of the conventional rolling process with the twin-roll casting and hot rolling process

Twin-roll cast strips are used as feedstock for producing conventionally rolled sheets where the final gauge thickness is achieved in only few rolling passes. It has been shown that twin roll casting is an efficient process for the generation of fine-grained strip as feedstock for sheet rolling. It combines casting and rolling in one processing step and therefore improves the processing efficiency of magnesium sheets [5].

Fig. 3. Solidification of the Metal during TRC

Alloy Development

One reason for the limitations associated with plastic deformation of magnesium alloys is the hexagonal close packed lattice structure of magnesium. It is accepted that the comparatively low formability of sheets is due to the limitation in the number of active deformation mechanisms, at least in comparison with the cubic metals. The low formability [6, 7] of magnesium alloys also has a significant impact on the processability during large scale deformation. Magnesium alloys containing rare earth elements could partially compensate for the poor formability. Magnesium sheet materials with small rare earth additions show a randomized texture and fine-grained

microstructure. Investigations show that this may be achieved with many rare earth additions including Nd, Y or Ce [8]. Fig. 4 shows a large decrease in the texture with the addition of Nd, Y and Ce compared with pure Mg as illustrated by the reduction in the intensity of (0002) pole figure. The maximum intensity of the (0002) pole figure decreased with the addition of Nd, Ce or Y with additions up to 0.2 at.%. However, with further increase in these alloy additions the intensity of the (0002) pole figure remained unchanged [8].

Fig. 4. Intensity of the (0002) pole figure illustrating the texture of magnesium alloys containing various amounts of Nd, Y and Ce [8].

This results in a better formability at room and elevated temperatures. The direct comparison between ZE10 (relatively randomised textured alloys) and AZ31 (strongly textured alloy) alloys show the influence of rare earth additions on the forming limit curve (FLC) at room temperature and 200°C is shown in Fig. 5.

Fig. 5. Influence of texture on the forming limit curves (FLC) of ZE10- and AZ31-alloys at room temperature and at 200°C.

The addition of rare earth elements improves the formability of these alloys making the alloys suitable for particularly high mechanical stress components. Since the corrosion resistance can be

improved, and the surface quality is sufficiently good these alloys may be usable in the vehicle exterior especially as sheet material. The addition of rare earth elements may be problematic due their strategic importance in many industrial applications and the tight supply situation. The rare earth elements are classified as critical raw materials in European Union [9] the recovery and recycling of these elements are associated with high financial costs and leads to dependence on imports for supply of these elements. In addition the production of the rare earth elements requires large expenditure of energy and can lead to environmental damage that should be avoided as part of sustainable material selection for industrial use. The aim of the present development is therefore to achieve the properties observed, such as texture randomisation, in the rare earth containing alloys or even surpass them by replacement or reduction in the use of rare earth additions. This will provide the basis for the economic production of high strength and ductile magnesium materials and components.

To overcome the drawbacks of Mg alloys sheets, e.g. limited formability at low temperature and strong mechanical anisotropy, it is essential to gain a fundamental understanding of the microstructure and texture evolution during the thermomechanical treatments. The texture randomisation and fine homogeneous grain structure lead to a significant improvement in mechanical properties and formability. The rare earth addition is an effective way to achieve texture randomisation and improvement of sheet formability at low temperature, but the Mg alloys sheets without RE elements are more beneficial in terms ecological and economic viewpoint. The addition of Ca into Mg-based alloys is known to be an effective method to improve the high temperature properties and the ignition resistance of magnesium alloys [10]. Recently it has been shown that the Ca addition leads to texture randomisation and grain refinement in Mg alloys after wrought processing, such as rolling [11, 12] or extrusion [13]. Kim et al. [11] showed that the Ca addition in Mg alloys with different Zn contents (Mg-1Zn and Mg-6Zn alloys) modify the sheet textures produced via twin roll casting. The as-rolled sheets show a splitting of basal poles toward the rolling direction (RD) of the sheet for sheets containing a lower Zn content, while the higher Zn containing alloy sheets show a basal pole split toward the transverse direction (TD) of sheet [11]. The recrystallization during annealing of these sheets leads to the development of a randomised texture with the basal pole splitting towards the TD for sheets regardless of the Zn content [11]. The Ca containing sheets have not only higher yield strength but also an excellent stretch formability comparable with that of Al 5052 alloy [12]. The authors suggested that the texture modification in the ZX11 and ZX61 sheets are related to the twin activities, including double twinning and extension twinning. The texture randomization effect is suggested to be due to the deformation bands consisting of twins as well as due to an increase in the of grains their basal pole rotating away from the normal direction towards the TD as a result of recovery and recrystallization. The Ca addition on the texture and microstructure of extruded Mg-Mn alloys was investigated by Stanford [13]. A significant texture randomisation was observed for the Ca containing Mg-Mn alloys, in which non-basal type texture developed [13]. It was suggested in the study that the texture modification observed in the Ca containing alloys was achieved due to the same reasons to those suggested for the RE containing alloys, attributing the cause of the texture randomisation to be the large atomic radius of Ca [13]. The texture randomisation of the extruded Mg-Mn-Ca alloys resulted in an improvement in tension-compression anisotropy. The presence of large Mg_2Ca particles caused a decrease in uniform elongation in alloys containing a relatively high concentration of Ca.

The strength of the Ca-added alloys can be increased further by an optimised aging hardening scheme. A small addition of Ca into ZK60 alloy induce a weakening of basal-type texture, which contributes to increase in formability, with a LDH (limiting dome height) of 5.6 mm in T4 condition [14]. After peak ageing treatment the twin roll cast and hot rolled sheet showed yield strength of ~ 290 MPa, which was attributed to formation of fine scale uniformly distributed MgZn based precipitates [14]. Hofstetter et al. [15] showed that the optimal design of processing conditions of the ZX alloys leads to a considerable improvement of the mechanical properties.

Through an optimised processing scheme designed through thermomechanical calculations consisting of a controlled treat treatment, Hofstetter et al. achieved a grain refinement in the Mg-1Zn-0.25Ca alloy. Fine scale uniformly distributed (Mg, Zn)₂Ca precipitates were achieved through the heat treatment which following thermomechanical processing gave rise to a very fine microstructure with average grain size of $\sim 2\mu\text{m}$. The refinement in grain size was attributed to the dynamic recrystallization and grain growth which was influenced by the presence of the particles causing possibly particle assisted recrystallization and retardation of grain growth [15]. The authors reported that this alloy, with relatively low concentration of alloying additions, showed a yield strength of 240 MPa and ultimate tensile strength 255 MPa and high ductility (fracture strain 27%) with low tension-compression anisotropy.

The Ca containing Mg alloys investigated for sheet applications deals mainly with Al-free alloys, e.g. Mg-Zn-Ca (ZX systems) and Mg-Mn-Ca (MX systems). The only previous investigation that reports on Ca containing Mg-Al alloys for wrought applications is the extruded Mg-3Al-3Ca-0.4Mn alloy with a fine grain size and high yield strength of 410 MPa [16]. However, there is no discussion on the effect of Ca on the texture randomisation of this alloy. The Ca addition into Mg-Al based alloys has been studied mainly focusing on its influence on the ignition resistance. A recent study [17], examined the influence of Ca addition to hot rolled sheets of twin roll cast AZ31 alloy on its mechanical properties, texture and formability. The microstructure and texture evolution of the AZX310 (Mg-3Al-1Zn-0.3Mn-0.5Ca (wt. %)) strip during the thermomechanical treatment is summarised in Fig. 6. The TRC strip shows eutectic lamellae structure at the mid-thickness area, i.e. mid-segregation, and a relatively strong texture due to a rolling deformation during the TRC with a maximum pole figure intensity for the (0002) of $P_{\text{max}} = 7.2$. During the subsequent hot rolling the mid-line segregation is changes to fine spheroidal particles with size of $0.5 \sim 1\mu\text{m}$. The AZX310 sheet contained a fine and uniform grain size distribution with an average grain size of $9.1\mu\text{m}$ and a high number density of fine Ca-rich particles distributed uniformly through the sheet thickness. Moreover, the AZX310 sheet shows a randomised texture with the basal poles split along the TD with a maximum pole figure intensity for the (0002) of $P_{\text{max}} = 2.7$. Based on the randomised texture and the homogeneously distributed fine particles, the AZX310 sheet shows excellent room temperature formability with the IE (Erichsen index) of 7.4. In addition, the AZX310 alloy sheets seem to be attractive for the industrial applications as the good corrosion resistance of the AZ31 alloy can be maintained in the modified alloys.

Conclusions

The development of a suitable alloy composition in conjunction with the appropriate manufacturing process can be used to realise commercially viable magnesium alloy sheet. Replacement of rare earth additions with Ca and the choice of twin roll casting as an efficient production method help to save energy during the production of sheet magnesium that is needed for improving the sustainability in vehicle production. This leads to further improvement in sustainability as it reduce weight of automobiles which can contribute to a significant reduction in energy consumption.

Fig. 6. Microstructure and texture of AZX310 alloy: (a) Optical micrograph along the longitudinal direction, and (b) recalculated (0002) pole figure, $P_{\max} = 7.2 \text{ m.r.d.}$ of the TRC strip. (c) Optical micrograph and (d) recalculated (0002) pole figure, $P_{\max} = 2.7 \text{ m.r.d.}$, of the TRC and rolled sheet. (adopted from [17]).

References

- [1] <http://www.autoherald.co.kr/news/articlePrint.html?idxno=12185>.
- [2] <http://www.businesskorea.co.kr/article/9538/mass-produced-magnesium-porsche-uses-poscos-mass-produced-magnesium-sheets-new-model>.
- [3] S.R. Agnew, in *Magnesium Technology 2002* (H.I. Kaplan (ed.)), TMS, Materials Park (2002), 169 – 174.
- [4] J. Bohlen, G. Kurz, S. Yi and D. Letzig, in *Advances in Wrought Magnesium Alloys* (C. Bettles, M. Barnett (eds.)), Woodhead Publ. Ltd. (2012), Oxford. 346 – 375.
- [5] F. Basson, D. Letzig, *Aluminium International Today*, (2010) November/December 19-21.
- [6] L. Stutz, J. Bohlen, G. Kurz, D. Letzig and K.U. Kainer, *Key Eng. Mater.* 473 (2011) 335 – 342.
- [7] C.E. Dreyer, W.V. Chiu, R.H. Wagoner and S.R. Agnew, *J. Mater. Process. Tech.* 210 (2010), 37-47.
- [8] K. Hantzsche, J. Bohlen, J. Wendt, K.U. Kainer, S.B. Yi and D. Letzig, *Scripta Mater.* 63 (2010) 725–730.
- [9] Critical raw materials for the EU: Report on the Ad-hoc working group on defining critical raw materials, version 30 July 2010: http://ec.europa.eu/enterprise/policies/raw-materials/files/docs/report-b_en.pdf.
- [10] B.-S You, W.-W Park and I.-S Chung, *Scripta Mater.*, 2000, Vol. 42, 1089-1094.
- [11] D.-W. Kim, B.-C. Suh, M.-S. Shim, J.H. Bae, D.H. Kim and Nack J. Kim, *Metall. Mater. Trans. A*, 44, (2013) 2950-2961.
- [12] B.-C. Suh, M.-S. Shim, K.S. Shin and Nack J. Kim, *Scripta Mater.* 2014, Vol. 84–85, 1–6.
- [13] N. Stanford, *Mater. Sci. Eng. A*, 2010, Vol. 528, 314–322.

- [14] T. Bhattacharjee, B.-C. Suh, T.T. Sasaki, T. Ohkubo, Nack J. Kim and K. Hono, *Mater. Sci. Eng. A*, 609 (2014) 154–160.
- [15] J. Hofstetter, M. Becker, E. Martinelli, A.M. Weinberg, B. Mingler, H. Kilian, S. Pogatscher, P.J. Uggowitzer and J.F. Löffler, *JOM*, 66, (2014) 566-572.
- [16] S.W. Xu, K. Oh-ishi, S. Kamado, F. Uchida, T. Homma and K. Hono, *Scripta Mater.* 65 (2011) 269-272.
- [17] S. Yi, D. Letzig, K.U. Kainer, O.D. Kwon, J.H. Park and J.J. Kim, in *The 10th international conference on Mg alloys and their applications*, (2015) submitted for publication at the conference.