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Potential and Advantages of Vertical Strip Casting for Production of High-Strength Aluminum-Magnesium Alloys

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Abstract. High-strength and recycling tolerable aluminum alloys make a significant contribution to weight reduction in modern lightweight construction. The advantages of aluminum alloys in terms of their low density combined with high strength can be significantly improved by the alloy composition. In contrast to the conventionally established process route, high-magnesium alloys can be produced using the twin-roll strip casting process. This allows additional process steps such as hot rolling and annealing to be drastically reduced in the economical production of near-net-shape strips, saving emissions and energy consumption. The strip casting process has already been applied to numerous aluminum alloys and enables their production, although the understanding of advanced alloys in this area is not yet fully understood because of its limited production in industry-related research due to the complexity of the process. However, transferring the high strength generated during rapid solidification into usable sheet performance remains challenging, especially at elevated Mg contents, where segregation, casting-related defects, and solute-affected recrystallization can limit ductility and processability. This study investigates the potential of a high-magnesium aluminum alloy produced by vertical strip casting. The properties of the alloy are correlated with the microstructural and mechanical characteristics and developed on the basis of an industrial reference alloy. For this purpose, an EN AW 5182 and an AlMg10 alloy were processed. The results show that high-magnesium alloys can be produced and processed using strip casting. In terms of the high-magnesium alloy, improved results can be achieved compared to the industrial EN AW 5182 alloy. Key findings: The strength of high-magnesium alloy is significantly above those of the EN-AW 5182 after strip casting enabling nearly 600 N/mm² tensile strength, but the final properties are below this potentially possible characteristic after strip casting, presumably due to non-ideal recrystallization and an insufficiently adapted process route including rolling and annealing parameters.

Introduction

High-strength aluminum alloys are essential for use in the automotive and aerospace industries. Their comparatively high strength and low density, combined with corrosion properties, enable their effective use in lightweight construction. Different alloy compositions, particularly those in the 6xxx and 7xxxx groups, account for the largest share of such applications. While 5xxx Al-Mg alloys generally show good corrosion resistance, high-Mg grades can become sensitized (β-phase precipitation at grain boundaries) during thermal exposure, increasing susceptibility to intergranular corrosion and environmentally assisted cracking [1]. The development of high-alloyed aluminum that does not need to be age-hardened is proving to be insufficiently using conventional manufacturing methods [2]. Negative effects with significantly higher alloying contents, such as segregation and demixing, as well as the formation of intermetallic phases, represent the current limitations [3]. To suppress these effects, vertical twin roll strip casting can be used [4]. This process is characterized by its high cooling rates in conjunction with the production of strips close to their final dimensions [5]. Furthermore, strip casting allows an increased usage of scrap due to the forced dissolution of accompanying elements as a result of rapid solidification and combines this with higher process speeds than is usual in conventional production [5, 6]. The aluminum-magnesium alloys that can currently be produced using existing technology are limited to contents of 4.5 up to 5.5 wt.-%. Higher alloy proportions lead to increased diffusion phenomena after casting into ingots and the formation of embrittling β-AlMg phases. The formation of the this phase is a critical aspect in terms of recrystallization behavior, which promotes nucleation and precipitations [7]. These have negative effects in the form of cracking and limited formability during further processing by hot or cold rolling. Aluminum alloys with magnesium contents of 10 wt.-% cannot therefore be produced economically and profitably [8]. The possibility of hot rolling can be used to circumvent the increased strength during forming can be achieved, but in conjunction with elevated temperatures and a high rolling degree, this contributes to the formation of a coarse-grained structure and negatively affects the mechanical properties in terms of grain size [9]. Due to the high solubility of magnesium in aluminum, increased proportions of intermetallic phases can be precipitated during equilibrium cooling, as occurs in conventional production. With a solubility of less than 1 wt.-% magnesium at room temperature, the formation of the embrittling β-AlMg phase is caused and the potential alloy cannot be handled [10]. With significantly increased cooling rates, as is the case in vertical strip casting, this effect can be almost completely avoided and supersaturated mixed crystals are formed [11]. The potential of vertical strip casting for these alloys in conjunction with exemplary thickness on an industrial scale has not been fully researched. The aim of this study is to present the material properties resulting from the strip casting process and further processing for high-strength aluminum-magnesium alloys in comparison to a conventional EN AW 5182 alloy also produced via strip casting as reference. This work focuses on the connection between rapid cooling and the resulting development of the microstructure, while correlating this with the mechanical characteristics of the full process. For this purpose, both a 5182 alloy and an AlMg10 alloy were produced using vertical two-roll strip casting and processed to a final thickness of 1.0 mm by hot and cold rolling. The final recrystallization annealing serves to produce a strip material that can be further processed. In addition to the microstructure, the grain structures and potentially embrittling intermetallic phases are characterized and correlated with the mechanical properties. The results of the process route starting with strip casting are presented for both alloys in order to enable a comparison of the potential using this manufacturing route with industrial standards.

Materials and Methods

Strip casting, rolling, recrystallization. A 5182-aluminum alloy and an AlMg10 alloy were produced using the vertical two-roll strip casting machine at the Institute for Metal Forming (IBF) at RWTH Aachen University. For this purpose, 120 kg of each alloy was melted in an induction furnace and cast onto two counter-rotating casting rolls with a width of 150 mm using a low-pressure furnace and casting system. The process was controlled by means of force control between the two casting rolls to ensure constant heat transfer between the casting roll surface and the solidifying melt. After this, the solidified strip was cooled in still air and prepared for hot rolling. To do this, strip sections were heated to 400°C for 10 minutes and then rolled from their initial thickness of 2.4 mm to 1.8 mm using a duo-roll setup, resulting in a 25 % reduction. This step serves to close any pores and cavities that may have formed as a result of rapid solidification during the strip casting process. In addition, the embrittling casting structure can thus be eliminated. In the final cold rolling process, the sheet sections were rolled to a final thickness of 1.0 mm in two passes, annealed at 360°C for 90 seconds, and cooled in still air. To achieve this state, as shown in Fig. 1, further processing is carried out with the corresponding process steps under the range of maximum solubility of magnesium in aluminum. Due to the lower degree of deformation during cold rolling in comparison of typical industrial processes, an increased annealing temperature of 360 °C was set for recrystallization. To avoid the formation of new intermediate phases, a short annealing time and rapid cooling were found to be advantageous.

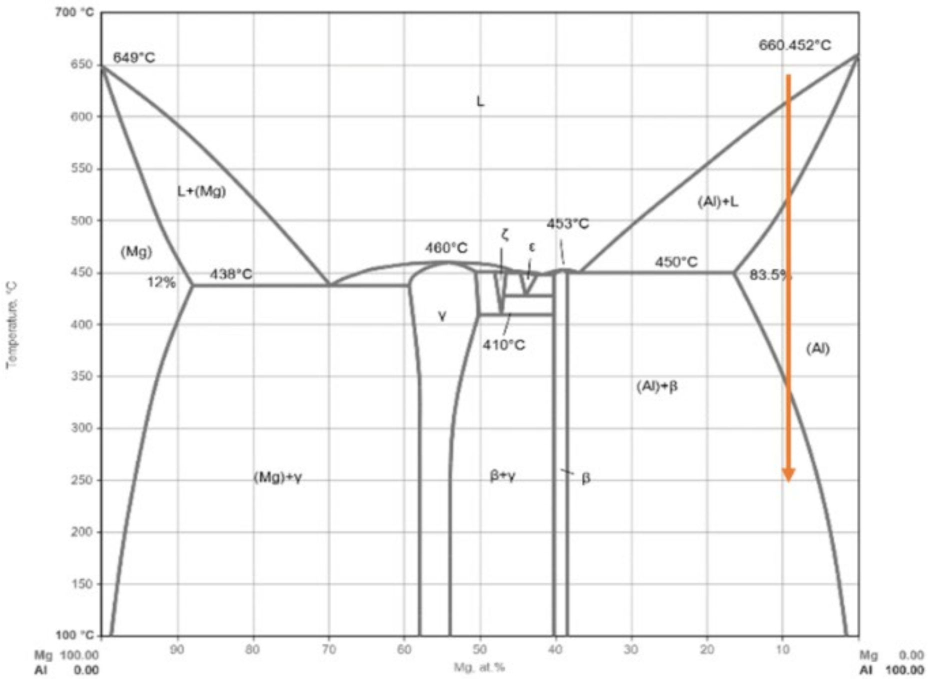


Fig. 1. Binary phase diagram in at.-% of Al-Mg with potential cooling route via strip casting [10]

To determine possible deviations in the alloyed elements, the chemical composition of the cast strip material was determined. This was determined using spark emission spectroscopy, which was performed with a Spectro Funkenspectrometer MAXx. Average values from at least 5 measurements are given.

Samples for microscopic and scanning electron microscopic examination were taken from the sheets produced in the various process steps. The microstructure was recorded on RD-ND (rolling and normal direction) using a Keyence VHX7000. Barker's etching agent was used to contrast the mechanically grinded and polished samples. These were etched at a voltage of 20 V for 30 seconds. The scanning electron microscope images were taken on a ThermoFisher Helios 5 Hydra UX. For this purpose, conductively embedded samples on RD-ND were also mechanically grinded, polished and slightly electrochemical polished for improved separation and visualization of grain structures. Overview images were recorded at an acceleration voltage of 5 kV using secondary and backscattered electrons. The different element distributions (spectra and linescans) were recorded at an acceleration voltage of 15 kV. The ElitePlus EDX detector from EDAX was used.

To determine the mechanical characteristics, A50 tensile specimens were cut out of the strip casting samples and the processed sheets in the rolling direction using water jet cutting. These were tested quasi-statically on a Zwick100 from the manufacturer ZwickRoell with video extensometer in accordance with DIN EN ISO 6892-1 [12]. To ensure reproducibility, three samples in longitudinal direction were tested with an strain rate of 0.001 1/s for each case.

Results and Discussions

Chemical composition. The measured chemical composition of both aluminum alloys after vertical two-roll strip casting is shown in Table 1. While the EN AW 5182 alloy is within the typical industrial limits, the potential high-magnesium alloy contains a magnesium content of 10.17 wt.-%. [13]. Other accompanying elements such as manganese or silicon are negligible because of their low quantities. Due to the minor deviations in the alloying elements, the differences in terms of microstructure and mechanical properties can primarily be reduced to the influence of the magnesium content.

Table 1. Chemical composition of produced and investigated aluminum alloys after strip casting in wt.%

	Mg	Si	Mn	Fe	Al
EN AW 5182	4.39	0.17	0.34	0.30	94.70
AlMg10	10.17	0.18	0.30	0.33	88.86

Mechanical and microscopic properties. The microstructure of the strip-cast alloy is shown in Fig. 2. Typical characteristics of the strip casting process can be seen here. In addition to the dendritic outer structure directed toward the center of the strip, globular portions are visible in the center of the strip. This microstructural subdivision arises from the solidification dynamics during strip casting. Dendritic structures nucleate and grow depending on the surface roughness of the casting rolls, extending into the molten metal. The rotation of the rolls subsequently directs these advancing dendrites toward the casting gap, influencing the final solidification morphology. There, the two strip shells that form are welded together due to the strip forming force. The residual melt still present in the center of the strip finally solidifies into globular crystals, as no further force acts on the solidifying strip.

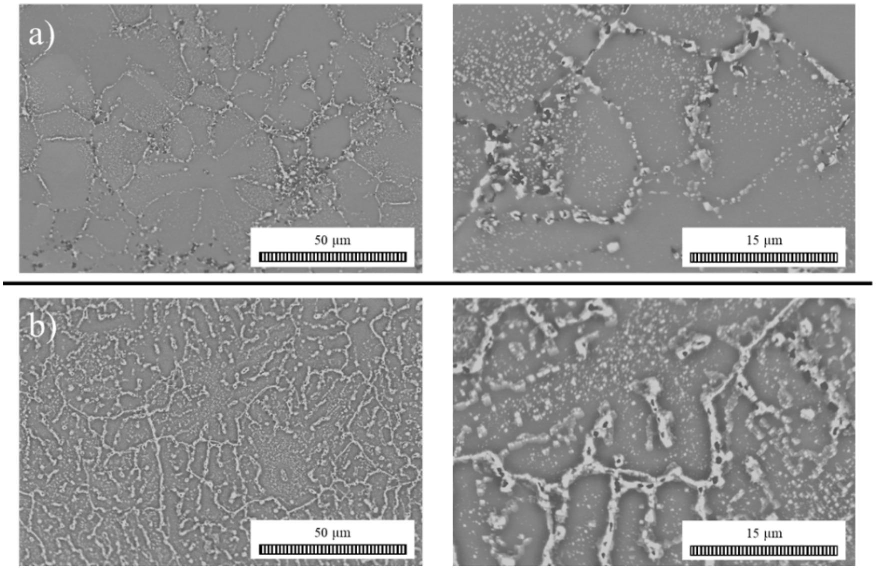
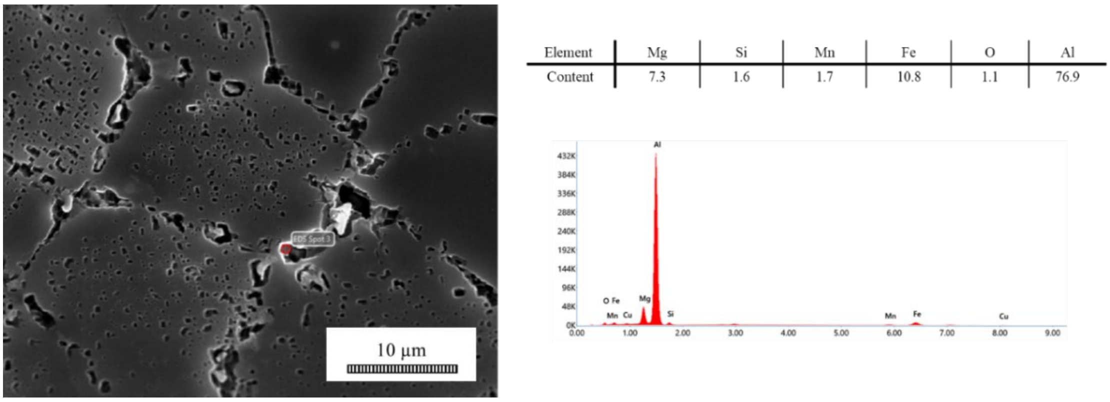


Fig. 2. Overview and detailed grain structure with boundaries a) near surface and b) in core with SEM (BSE) of EN AW 5182 alloy

Due to slower cooling in the middle part of the strip compared to the outer band shells, more pronounced segregation occurs at the grain boundaries. The grain boundaries in the middle section of the strip exhibit magnesium concentrations of over 7 wt.-% Magnesium, with simultaneous enrichment of silicon, iron, and manganese as it can be seen in Fig. 3.



Element	Mg	Si	Mn	Fe	O	Al
Content	7.3	1.6	1.7	10.8	1.1	76.9

Fig. 3. EDS measurement with chemical composition of segregation for EN AW 5182

This is also evident in the distribution of alloying elements across the sheet thickness as shown in Fig. 4. The line scan starting at the sheet surface shows almost no fluctuations in magnesium concentration across the first area of directional solidification. After the transition to the globular structure in the middle of the strip, there are increased deviations, which can be attributed to the slowed cooling. Between the globularly solidified grains, the described precipitates are partially visible at the grain boundaries.

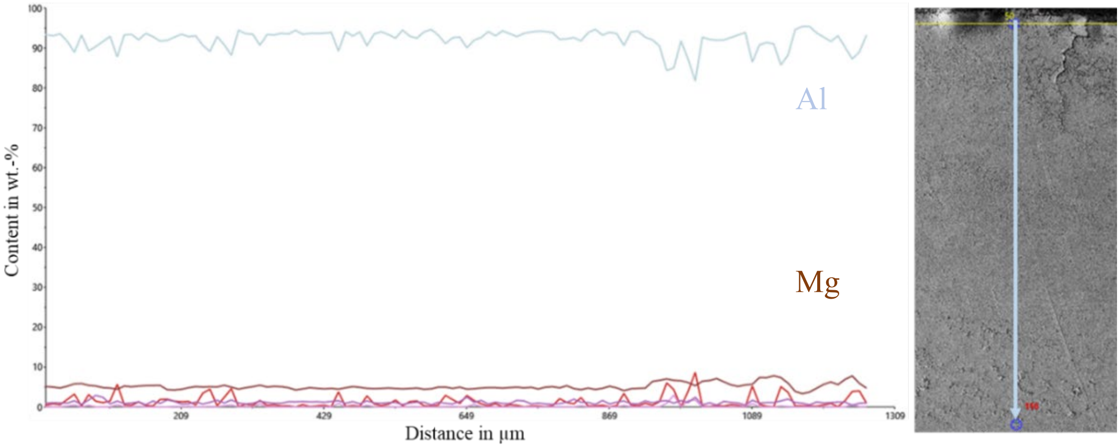


Fig.4. Linescan with element distribution via normal direction of EN AW 5182

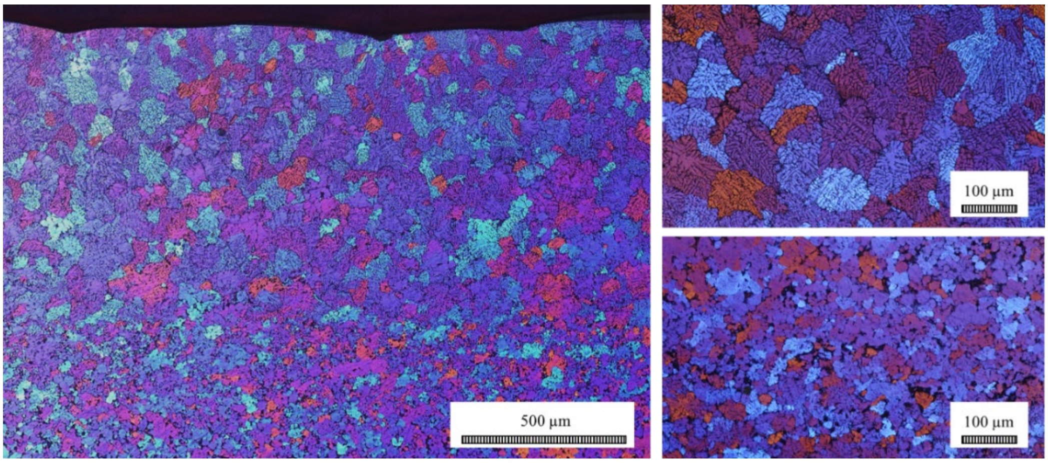


Fig. 5. Microscopic overview of microstructure with detailed images of surface and core area of EN AW 5182

A similar behavior during solidification can also be observed in the high-magnesium alloy. The grain structure around the outer area of the strip has a homogeneous structure and grain size. The core area of the strip is characterized by a globular grain shape and stronger segregation. Visually, similar differences between the center and outer regions can be detected as seen in Fig. 6.

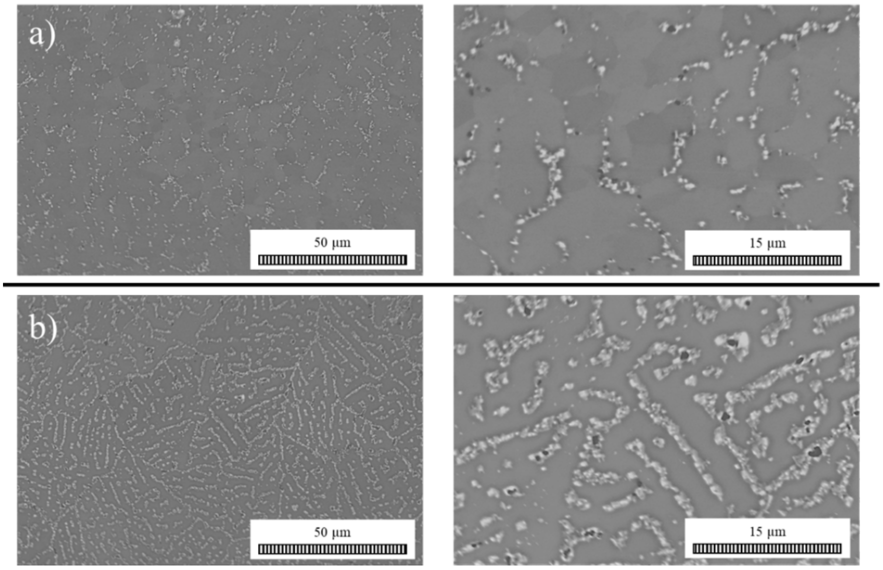
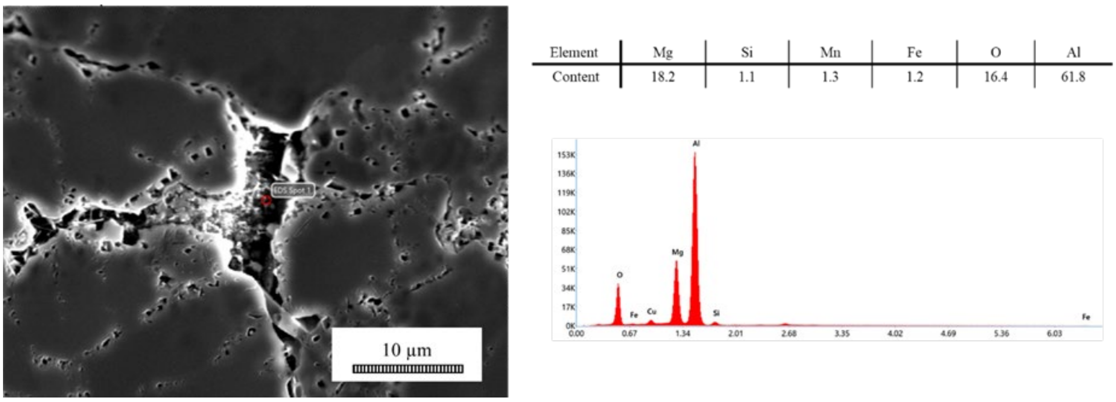


Fig. 6. Overview and detailed grain structure with boundaries a) near surface and b) in core with SEM (BSE) of AlMg10

This also shows an enrichment of alloying elements at the grain boundaries as shown in Fig. 7. With a magnesium content of 18.2 wt.%, which is significantly higher than that of the EN AW 5182 alloy and the amount of the alloy. Furthermore, increased oxygen content can be detected compared to the EN AW 5182 alloy. In addition to possible effects caused by slight electrochemical polishing, these can be attributed to oxide compounds in the magnesium source material and oxidation during the casting process.



Element	Mg	Si	Mn	Fe	O	Al
Content	18.2	1.1	1.3	1.2	16.4	61.8

Fig.7. EDS measurement with chemical composition of segregation for AlMg10

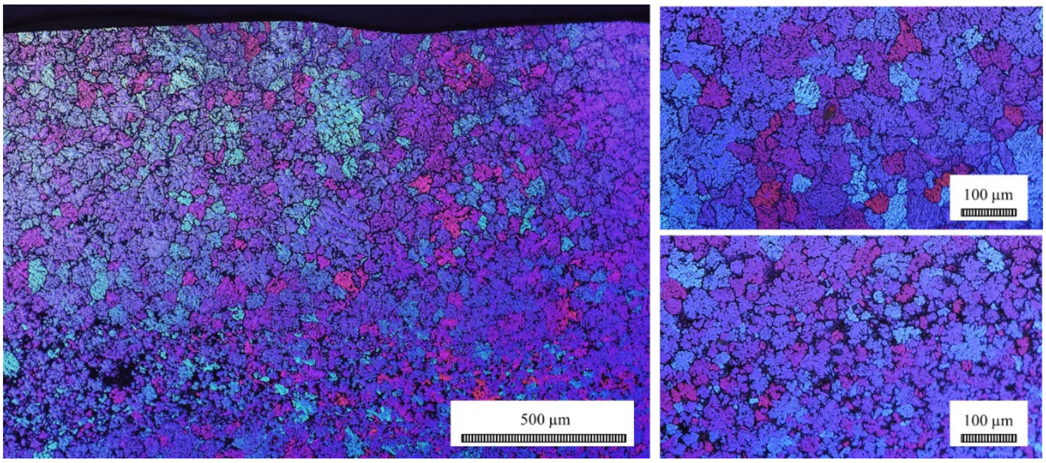


Fig. 8. Microscopic overview of microstructure with detailed images of surface and core area of AlMg10

This finding can be confirmed by characterizing the respective element distributions. The line scan, starting at the strip surface, show no significant fluctuations in alloy content as they progress toward the center of the strip. The differences in concentration are particularly noticeable in the high-magnesium alloy, where they are less than 1 wt.%. Starting from the strip surface, a slight decrease in concentration of magnesium can be seen from around 800 µm. This is due to the different solidification processes involved in strip casting. Within the outer strip shell up to approximately 500 µm, the distribution is almost homogeneous. Due to the faster solidification, no diffusion processes can take place and homogeneously distributed mixed crystals are present in the material. In the middle range from 500 µm, an initial decrease in magnesium concentration to approximately 9 wt.-% can be observed. Isolated fluctuations and the reduced concentration indicate a change in solidification behavior and slower cooling due to residual heat still present. Diffusion processes can take place on a small scale, leading to a slight increase in magnesium enrichment at the grain boundaries. This observation is consistent with the microstructures.

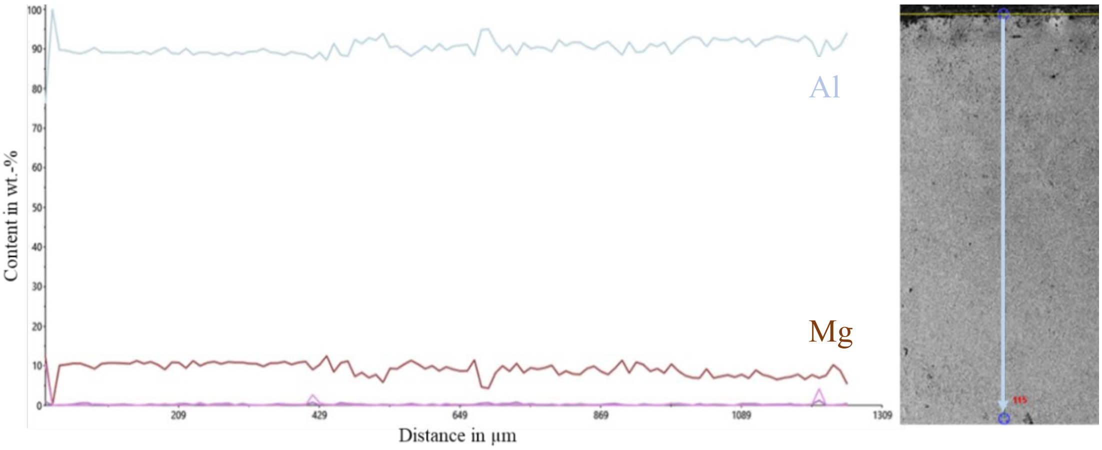


Fig. 9. Linescan with element distribution via normal direction of AlMg10

The phenomenon of center segregation, which occurs in other strip casted alloys, especially those containing iron and silicon, cannot be observed. This phenomenon is based on the remaining melt, which briefly enriches itself with the alloying elements. Due to the maximum solubility of 18 wt.%, even the residual melt in the center of the strip and a sufficiently high cooling rate suppress formation of segregation ovoer the strip thickness.

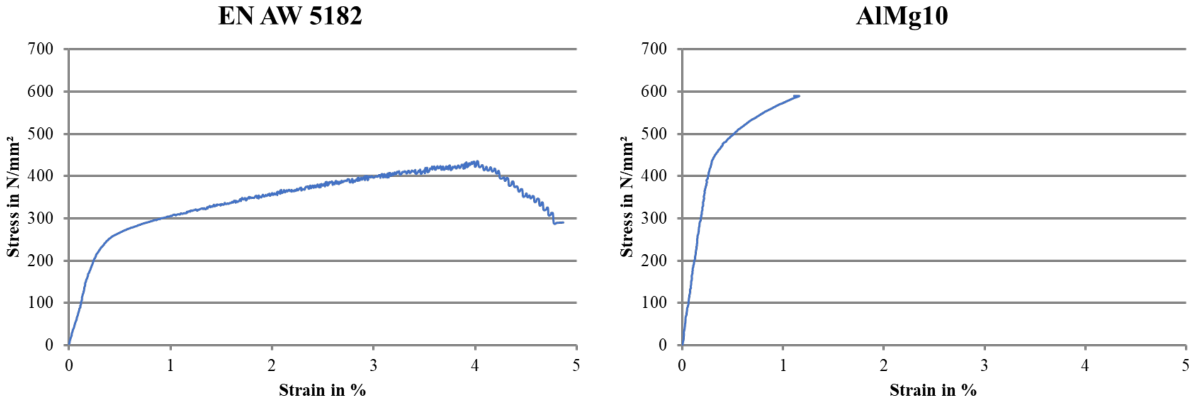


Fig. 10. Stress-strain curves of EN AW 5182 alloy and AlMg10 after strip casting

These results are confirmed by the mechanical property characterization shown in Fig. 10. A comparison of the two alloys reveals the expected stress-strain curves. With a yield strength of 250 MPa and a tensile strength of 425 MPa, the EN AW 5182 alloy exhibits the maximum achievable characteristic values due to the almost complete dissolution of the alloying elements. In comparison, significantly higher values are observed for both the yield strength and the tensile strength of the high-magnesium alloy. A yield strength of 450 MPa and a tensile strength of 590 MPa illustrate the effect of the significantly more pronounced solid solution strengthening. This mechanism is accompanied by a reduction in total elongation after failure, which, at 1.2% is significantly lower than that of the EN AW 5182 alloy. Furthermore, the decrease in total elongation after failure can be attributed to the presence of casting defects. Strip-cast materials typically exhibit solidification voids and micro-pores in the center of the strip, which also reduce the maximum elongation. This can be seen in the EN AW 5182 alloy, which has an elongation at break of 12% compared to standard processes. After cold rolling and recrystallization annealing, a fine-grained microstructure continues to develop in both alloys. As can be seen in Fig. 11 and 12, both alloys in general exhibit coarser structures at the grain boundaries.

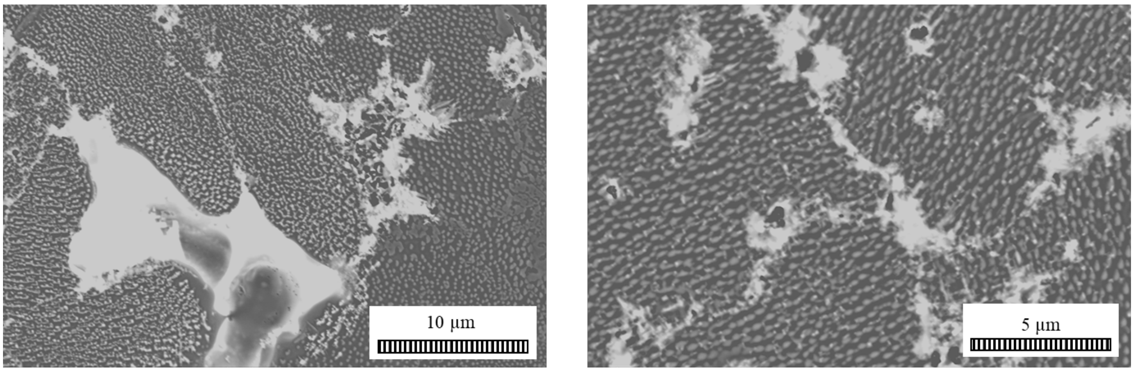


Fig. 11. Grain structure and boundaries with SEM of EN AW 5182

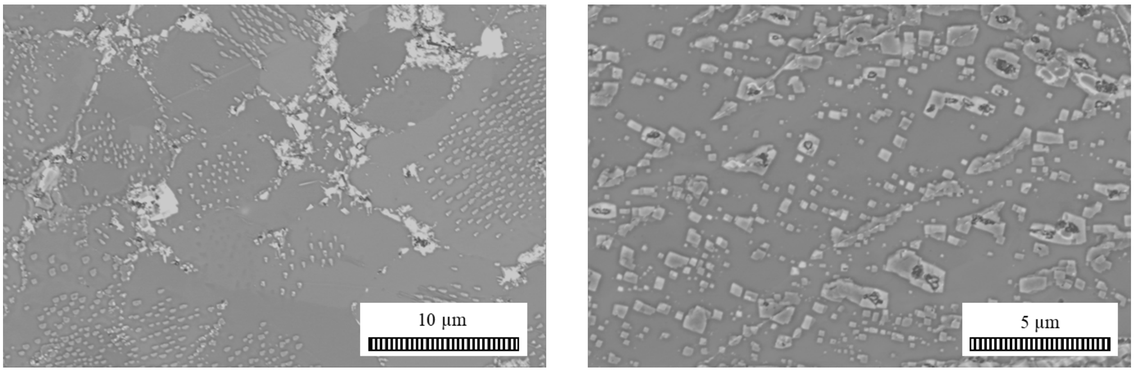


Fig. 12. Grain structure and boundaries with SEM of AlMg10

A comparison of the two alloys reveals differences in terms of grain structure and the presence of segregation phenomena. The EN AW 5182 alloy exhibits coarser structures at the grain boundaries, which extend over a larger area. In contrast, the high-magnesium alloy exhibits significantly less pronounced features of this type. The structures are more finely distributed and range in size up to 10 µm. The finer grain structure, which can also be seen in Fig. 13, can be explained by the increased proportion of alloying elements. The recrystallization behavior, which depends on the chemical composition, the introduced deformation, and the thermal energy, is inhibited by the high proportion of magnesium in the mixed crystals. With an annealing time of 90 seconds, grain growth after recrystallization cannot proceed to the same extent as in the EN AW 5182 alloy.

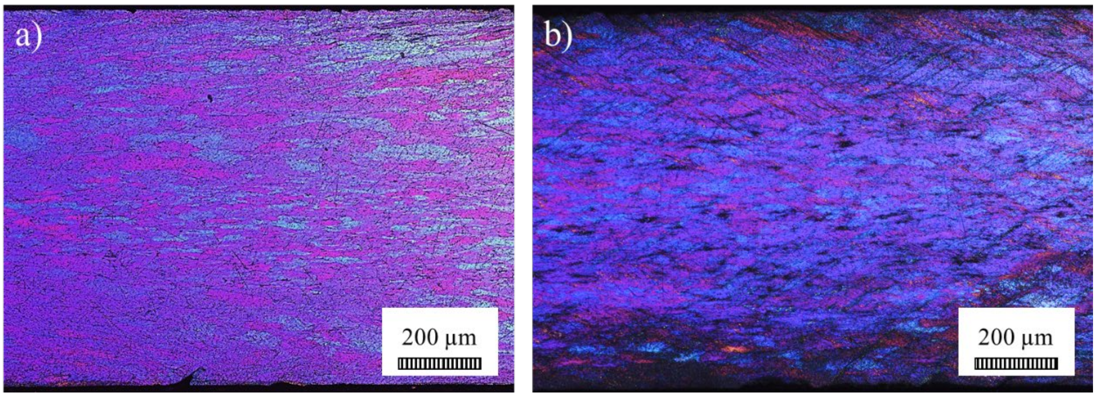


Fig. 13. Microscopic overview of microstructure of a) EN AW 5182 and b) AlMg10

Furthermore, this grain structure a explains the stress-strain curves shown in Fig. 14. With a yield strength of 280 MPa and a tensile strength of 360 MPa, the processed EN AW 5182 alloy is within standard specifications. Compared to the strip-cast starting material, the high-magnesium alloy also has a yield strength of 300 MPa and a tensile strength of 410 MPa. On the one hand, these values are above those of the EN AW 5182 alloy, but on the other hand, they are significantly below the initial properties after strip casting. With a maximum elongation of 2.8%, the plasticity shows improved values. Various factors may be responsible for these properties: The high-magnesium alloy has a finer-grained structure with increased segregation at the grain boundaries. According to the Hall-Petch relationship, the ideal grain size for a medium-magnesium alloy is <50 µm [14]. This is not achieved when viewed under light microscope, which also leads to reduced strength. Furthermore, if the degree of deformation during rolling is not sufficiently high and casting defects are still present, this can lead to easier crack formation and propagation.

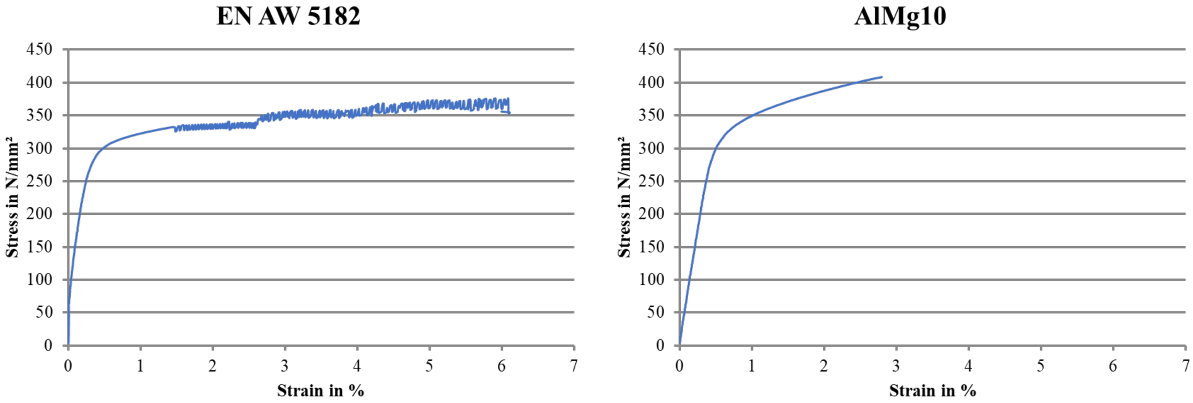


Fig. 14. Stress-strain curves of EN AW 5182 alloy and AlMg10 after final annealing

Summary

The vertical strip casting process enables an efficient process route for producing alloys that cannot be manufactured using conventional methods. This route allows significantly higher alloy contents and the associated improvements in mechanical properties. In addition to economic and processrelated cost reductions, strip casting is characterized by high cooling rates, enabling the production of strips with final thicknesses of around 1 mm using minimal rolling and annealing steps. With a magnesium content of 10 wt.%, higher strengths can be achieved compared to conventionally producible alloys. A tensile strength of 410 MPa with a fracture strain of 2.8 % demonstrates the microstructure development based on the EN AW 5182 alloy under identical processing. Despite an almost homogeneous chemical composition across the sheet thickness, differences in initial properties remain evident. The possible tensile strength of 590 MPa achieved directly after strip casting cannot be retained during further processing. Inhomogeneous grain sizes and varying solidification structures reduce the mechanical properties, and the recrystallized grain structure is not fully developed. Also, the hot rolling parameters combined with the reduced deformation during cold rolling inhibit recrystallization kinetics and influence the final microstructure decisively. This work highlights the potential of strip casting for producing such alloys and provides insights into the resulting microstructures. Further research should focus on optimizing subsequent process and annealing parameters to preserve the high strength after strip casting and achieve an ideal grain size and recrystallization state. Adjusting strip casting parameters and alloy design, including increased levels of accompanying elements, offers further potential to improve homogeneity, promote recrystallization, and enable recycling-tolerant alloys with higher magnesium contents.

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