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Asymmetric Twin-Roll Casting of an Al-Mg-Si-Alloy

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Abstract. The industrial application of high-alloyed Al-Mg-Si alloys for the production of thin strips by means of twin-roll casting is limited due to the structural inhomogeneity and segregation formation. To reach the highest mechanical properties of the finished product, a direct influence on the strip formation conditions during the twin-roll casting can be applied. Analogous to the asymmetric rolling process, additional shear stresses were created in the strip forming zone by using different circumferential velocities and torques of the caster rolls. To provide the asymmetric process conditions, only one caster roll was left driven and the second one was left idling during the casting process. The microstructure and the mechanical properties of the strips in the as-cast state as well as after the homogenization and subsequent age-hardening were analyzed. A comparison of the test results showed a positive influence of the asymmetry conditions on the strips' properties.

Introduction

Lightweight engineering is one of the most promising and innovative directions of modern manufacturing and science. The use of durable and light constructions in the automotive industry allows the weight of vehicles, their corresponding fuel consumption and their harmful pollutions to be significantly reduced. Al-Mg-Si alloys can reach, in the age-hardened state, a tensile strength over 300 MPa while simultaneously having high corrosion resistance, good weldability and ductility and reasonable pricing, making them good candidates for lightweight applications.

Additionally, considerable energy- and resource-saving effects can be reached by the application of novel, environmentally-friendly metallurgical technologies, such as twin-roll casting (TRC), for thin strip production. TRC allows for the production of flat products directly from the melt. Its advantages are a short production chain, low energy and material consumption, as well as smaller production areas and a decreased number of servicing personnel [1]. Presently, the industrial application of high-alloyed Al-Mg-Si alloys for the production of thin strips by means of TRC is limited. The main restrictions for TRC of such alloys are a wide temperature range of solidification, higher roll separating force, structural inhomogeneity and segregation formation [2, 3].

The possibility of producing thin strips of high-strength aluminum alloys by means of TRC was shown in [4] using EN AW-6082 and EN AW-7020 alloys. However, the EN AW-6082 alloy strips did not meet the standard requirements in terms of ductility in their initial twin-roll cast state. This was due to a cast non-recrystallized microstructure in the surface layers and a high degree of segregation.

To minimize the named microstructural features and to reach the highest mechanical properties of the finished product of Al-Mg-Si alloys, a complex processing procedure is required after the TRC [5, 6]. Alternatively, a direct influence on the strip formation conditions during the TRC can be applied. This can be realized through an adaptation of process parameters, as well as a change of the stress/strain state in the strip forming zone (see Fig. 1).

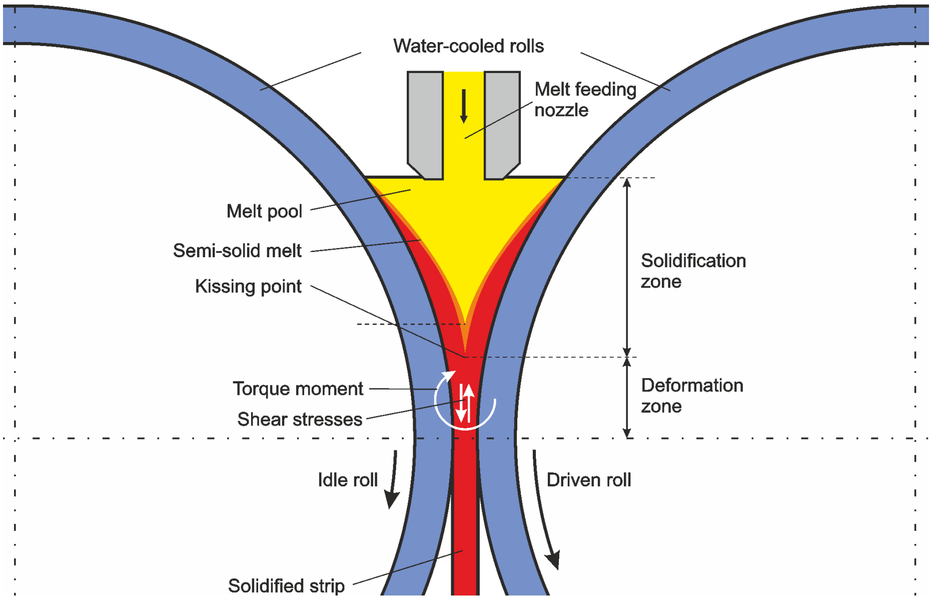

Fig. 1. Basic schematic of the asymmetric twin-roll casting

Creation of the asymmetry conditions and the application of additional shear stresses in the forming zone is a well-known method widely used in rolling. It results in intense grain refinement as well as lower roll separating forces under the same forming conditions [7, 8]. Differential rotation speed of both rolls or the use of one driving and one idle roll (kinematic asymmetry), differential diameter of rolls (geometric asymmetry) and the use of different friction coefficients on the contact surface between the sheet and two rolls are all possible methods to achieve an asymmetry in the rolling process [9]. Lapovok et al. have compared the effect of rolling with two driven rolls as well as asymmetric rolling with one driven and one idle roll on the microstructure, texture and mechanical properties of IF steel [10].

The influence of asymmetric rolling on the properties, texture and microstructure of twin-roll cast strips is already widely studied [11-13]. The main effects of such treatment resulted in the grain refinement, reduction of the recrystallization temperature and formation of distinct shear texture.

Analogous to the asymmetric rolling process, additional shear stresses can be created in the strip forming zone by utilizing different circumferential velocities of the caster rolls. In the case of TRC, an additional effect can be realized by suppressing near-surface and centerline segregation formation in the strips. One of the known projects concerning the asymmetric TRC was performed by Krupp Stahl AG and Nippon Metal Industry [14]. In 1986, they developed a twin-roll caster with casting rolls of different diameters. By means of this unit, strips of stainless steel of 1 mm to 4 mm thickness were produced at a speed of 40 m/min. Another twin-roll caster with different roll diameters was developed and built for scientific research by Haga et al. [15]. Aluminum alloy strips of 4.5 mm thickness were produced at a speed of 30 m/min.

Compared to the asymmetric TRC with different roll diameters, the process with different roll speeds and with one driven roll has not been examined. The only investigations known, dedicated to the asymmetric TRC with different roll speeds, have been carried out at Tsinghua University [16, 17]. Using a horizontal asymmetric twin-roll caster, strips of AZ31 magnesium alloy with a thickness of 6 mm and a width of 600 mm were cast. An inhomogeneous microstructure and different characteristics of dendrites were observed in the produced strips. Near the faster roll, the solidified dendrites were elongated due to the strong plastic deformation in the strip forming zone and the higher temperature. The core of the band consisted of thick dendrites due to the lower cooling rates. Near the surface of the slower roll, the formation of thin dendrites was promoted by a higher cooling rate. The band structure near the top roll also showed deformation caused by shear stresses.

The aim of the present work is the comparative analysis of the microstructure and properties of Al-Mg-Si alloy strips manufactured by means of symmetric and asymmetric TRC.

Experimental Procedure

Thin strips of an Al-Mg-Si alloy were manufactured by means of symmetric and asymmetric TRC. The manufacturing of the aluminum alloy strips, alloyed with 0.93 wt% Si, 0.66 wt% Mg and 0.49 wt% Mn, were carried out using the laboratory twin-roll caster at the Chair of Materials Science of Paderborn University. The unit consists of two 370 mm diameter, internally water-cooled rolls and has a vertical melt feeding scheme [18]. The process parameters securing the steady-state manufacture of the strips were chosen based on earlier investigations [4, 5] and remained unchanged for the duration of the study. The constant process parameters used in the experimental study were a finished strip thickness of 3.0 mm, strip formation zone length of 45 mm, casting rate of 3.9 m/min and casting temperature of 670 °C. To provide the asymmetric process conditions, the laboratory twin-roll caster was modified. In the experimental series on the asymmetric TRC, only one caster roll was left driven and the second was left idling during the process. This scheme allowed a speed difference on the rolls' surfaces to be obtained and, consequently, an additional torque moment in the strip formation zone to be created. During the twin-roll cast experiments a roll separating force was measured and amounted by symmetric and asymmetric TRC to 180 kN and 140 kN correspondingly.

The sections of the strips which had a good surface quality and did not have noticeable casting defects were used for further investigations. Since the state "F – as fabricated" isn't specified for the alloys of Al-Si-Mg-system, the samples were subjected to an age-hardening heat treatment in order to reach the advanced strength of Al-Mg-Si alloy in the "T6" state. The treatment consisted of homogenization combined with solution annealing, followed by quenching and artificial aging. For this purpose, the strips' sections were heated to 560 °C in a conduction heat furnace at a heating speed of 25 K/h and soaked at this temperature for 12 h. Subsequently, the sections were quenched in water and soaked in the furnace for 4 h at a temperature of 180 °C. To analyze the strips' microstructure in the as-cast state as well as after the heat treatment, microsections were prepared. The sections were taken from a plane parallel to the TRC direction, ground, polished and etched according to Barker to reveal the grain structure. The observation of the microstructure in polarized light using a digital light microscope (Keyence VHX5000) followed the specimen preparation. For analysis of the strips' mechanical properties after age-hardening, the machined specimens were subjected to uniaxial tensile testing at ambient temperature with a strain rate of 0.001 s^{-1} in accordance with ISO 6892-1:2009.

Results

The micrographs presented in Fig. 2 show the grain structure of the symmetric and asymmetric twin-roll cast strips. The layered structure, characteristic for the twin-roll cast material, can be detected over the width of the strips. Two zones of distorted dendritic structures were found in the near-surface regions of both strips, a layer of fine equiaxed grains is seen near the core and two layers of coarse dendritic grains are located between these zones (Fig. 2a, b). Inclined bands near the surface of the strips indicate the plastic strain during the TRC. The dendritic structure primarily formed in the solidification zone perpendicular to the rolls' surfaces was strained towards the casting direction. At the same time, a significant difference can be seen between the shape of grains in the symmetric and asymmetric twin-roll cast strips. The grain structure in both surface layers of the symmetric cast strip is inclined to the strip outlet direction. On the contrary, only the grains in the surface area that were in contact with the faster roll in the asymmetric cast strip (see Fig. 2e) are inclined in this direction, while the grains close to the surface of the slower roll (see Fig. 2c) are distorted in the opposite direction. A transition layer of uniformly elongated grains without any inclinations can be seen between them. Black areas as depicted in Fig. 2d can be seen in the middle of both strips, indicating the centerline segregations. Their level, however, is very similar in both the asymmetric and the symmetric cast strips.

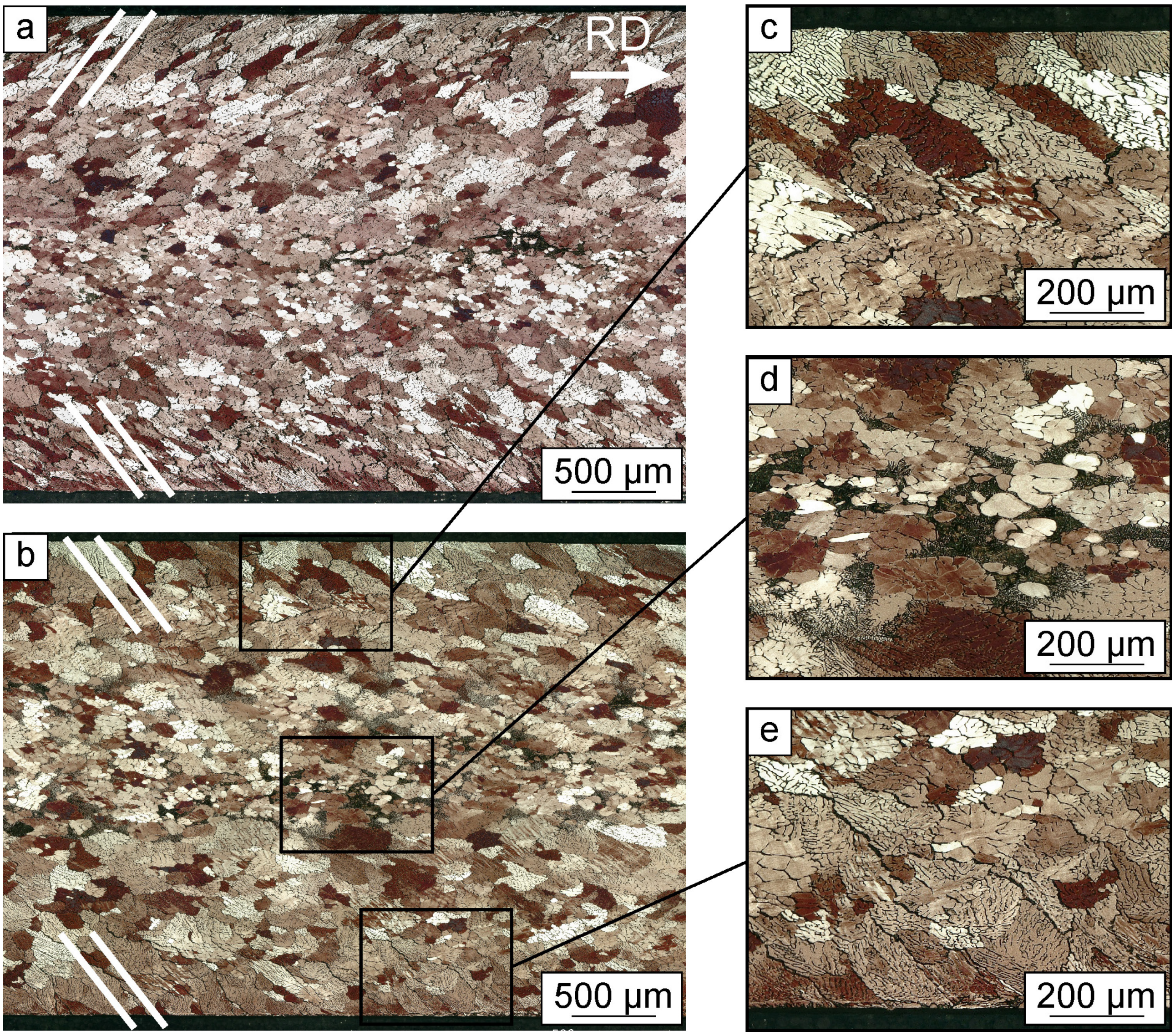

Fig. 2. The grain structure of symmetric (a) and asymmetric (b-e) twin-roll cast strips in as-cast condition. c – near the surface of slower roll, d – in the strip core, e – near the surface of faster roll. RD – rolling direction. White lines indicate the inclination of the grains

Figure 3 shows the microstructure of the asymmetric and symmetric cast strips after the heat treatment. The microstructure has become more homogeneous, and coarse round recrystallized grains have formed. In the middle, the remaining traces of the centerline segregations can be seen. The difference in the grain structure in the strips after the heat treatment is clearly seen in Fig. 3. While the symmetric cast strip retains the deformational pattern and the grains are still elongated in the rolling direction, the asymmetric cast strip possesses mostly equiaxed grains without any preferred elongation direction over the whole thickness.

The results of the tensile tests of the strips after symmetric and asymmetric TRC and age-hardening are presented in Table 1. An improvement in the tensile strength of the strips by applying asymmetric conditions at TRC is noted. The ultimate tensile strength and yield strength of the asymmetric strips are correspondingly 15 % and 21 % higher than those of the symmetric cast ones. At the same time, the elongation at fracture remains relatively low, which can be explained by the residual cast structure of the strip material [4].

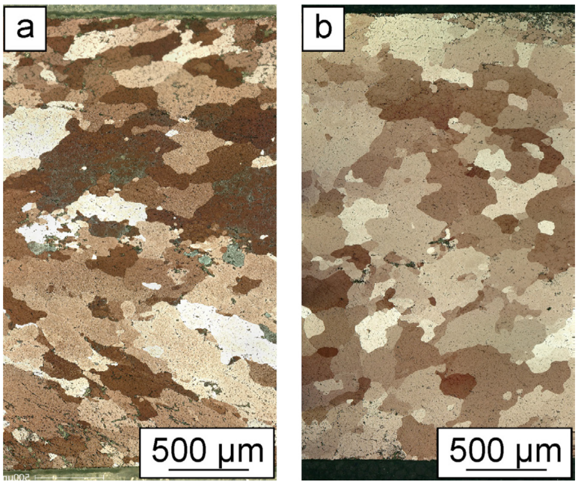

Fig. 3. The grain structure of symmetric (a) and asymmetric (b) twin-roll cast strips in age-hardened state

Table 1. Mechanical properties of the twin-roll cast strips in age-hardened state

Condition	Symmetric twin-roll cast and age-hardened	Asymmetric twin-roll cast and age-hardened
Ultimate tensile strength, [MPa]	260±4	298±6
Yield strength, [MPa]	239±4	288±5
Elongation at fracture, [%]	2±1	2±1

Discussion

As the circumferential speeds and torque of the rolls during the TRC are different, the metal in the strip formation zone undergoes additional shear stresses and deformation. First, the shear stresses concentrate in the forming zone, where the speed difference between the rolls is translated from roll to roll via the already-solidified strip. As the strip is slipped to the rolls' surface, additional shear stresses exist in the metal along with the compressive stresses from rolling reduction. This can explain the decrease in the roll separation force during the asymmetric TRC.

The dendritic grains in this case undergo additional straining; however, unlike the symmetric TRC, the grains are not elongated in the rolling direction. This results in an equiaxed grain structure in the strips after the homogenization annealing. The grains in this case are slightly finer, which leads to the improved strength properties. At the same time, the more intensive recrystallization induced by shear deformation during TRC causes the amount of residual centerline and near-surface segregations to be reduced. This has an additional positive effect on the strength properties of the strips.

It should be mentioned, that the level of differences in the rolls' speeds and, correspondingly, the level of applied shear stresses, is limited. Using the scheme with one idle roll, the difference is determined by its resistance to rotation. To achieve higher speed differences and greater effects on the grain refinement, as well as on the suppression of segregates formation, the second roll must also be driven with a prescribed speed difference from the other roll. This should be subject of further investigations.

Conclusions

Thin strips of an Al-Mg-Si alloy were manufactured by means of symmetric and asymmetric twin-roll casting. The speed and torque difference on the rolls' surfaces and, consequently, additional shear stresses in the strip formation zone, were reached using one driven and one idle roll. The microstructures of the symmetric and asymmetric cast strips possess significant differences caused by the additional shear deformation. This results in a slight grain refinement and allows an equiaxed grain structure to be reached during the subsequent annealing. The strength of the strips is positively influenced as well.

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