Light Metals 2014
Edited by: John Grandfield
TMS (The Minerals, Metals & Materials Society), 2014

INFLUENCE OF THE TWIN-ROLL CASTING PARAMETERS ON THE MICROSEGREGATION IN THIN STRIPS OF THE ALUMINIUM ALLOY EN AW-6082

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Keywords: Twin-roll casting, Aluminium alloys, Microsegregation, Microstructure, EPMA, EN AW-6082

Abstract

Twin-roll casting is a modern process for the production of thin strips directly from the melt with a minimum of energy and material consumption. Nowadays, lightweight thin strips of age-hardenable aluminium alloys with medium and high strength are widely used in the machine building and construction. However, the wide application of twin-roll casting technology for the strip production from high-alloyed 6XXX- and 7XXX-series aluminum alloys is limited due to the presence of characteristic near-surface microsegregation in the strips caused by non-uniform deformation over their thickness in twin-roll caster. Microsegregation leads to inhomogeneous microstructure of the strips and consequently deteriorates their mechanical characteristics, corrosion resistance and surface quality. This paper focuses on the influence of twin-roll casting speed on the microsegregation in strips of the aluminum alloy EN AW-6082. Analysis of 3 mm thickness strips obtained by twin-roll casting at different speeds is carried out using metallographic and electron microscopy methods.

Introduction

Twin-roll casting of thin strips and sheets is one of the most environmentally friendly and energy-efficient metallurgical technologies. This is due to the reduction in the number of required heating cycles and the amount of rolling operations during the manufacture from the melt to the finished product [1]. The most important directions of its development are in an increasing productivity and an extension of the materials range to produce strips; including high-strength age-hardening aluminum alloys. Due to their high strength of more than 300 MPa in the age-hardened state, such strips are widely used in various industries and in building construction. Their application in lightweight constructions in modern vehicles is of great interest too. Their use can significantly reduce the emission of greenhouse gases during the vehicle’s operation. At present, nearly three quarters of all the products of wrought aluminum alloys are made of 6xxx-series alloys of the Al-Mg-Si system [2]. Their advantages are good ductility combined with high strength, high corrosion resistance and relatively low cost. High mechanical properties of products made of 6xxx-series alloys are provided by a large number of alloying elements having different melting points. The differences between the liquidus and solidus temperatures of these alloys can reach 100 °C. The main impediment to the industrial use of the twin-roll casting technology for such alloys are poor mechanical properties of the produced thin strips due to microstructural defects, such as near-surface cracks and segregation.

The possibility of producing thin strips of high-strength aluminum alloys by means of twin-roll casting was shown in [3] by using the example of the 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 is due to a cast non-recrystallized microstructure in the surface layers and a high degree of segregation. Axial macrosegregation and near-surface microsegregation are the most pronounced microstructural defects in twin-rolled cast strips produced from highly-alloyed aluminum alloys [4]. Increasing the twin-roll caster productivity requires increasing the casting speed. However, reach a certain critical casting speed results in the formation of surface segregates in the strips [5]. Despite active melt mixing and rapidly cooling the metal in the twin-roll caster, this effect cannot be avoided. Similarly, increasing the casting speed as well as the number of alloying elements promotes the formation of centerline segregates [6]. Microsegregations and inclusions have a substantial influence on the microstructure and mechanical properties of the strips, both in their initial state as well as after heat treatment. Heterogeneous microstructures may undergo significant changes depending on the conditions of the heat treatment [7]. As a result of the microsegregations, an inhomogeneity of the strips mechanical properties occurs across their width and along their length and the formation of microcracks is initiated. The near-surface microsegregations in strips of the 6xxx-series alloys have a significant influence on the corrosion resistance. By using the example of the alloys 6016 and 6082, it was observed that the centers of microsegregations weaken the naturally formed oxide surface layers and serve as preferable sites for pitting corrosion [8]. Thus, for twin-roll cast strips an additional passivation treatment is necessary. At present, the main methods for studying the strips’ microstructure and microsegregations are the analysis of microsections, spectral analysis of the chemical and phase compositions and analyses of heterogeneous zones by scanning (SEM) and transmission electron microscopy (TEM). In recent years, digital analysis of micrographic images has also become increasingly applied.

The mechanism of segregation was investigated in detail by Forbord et al. [9] using strips of the 5052 alloy. During the material’s crystallization between the solidified material shells and the rolls surfaces, gaps form which lead to low pressure zones in the cast alloy adjacent to the gaps. Due to this low pressure, the interdendritic liquid squeezes into these gaps through the channels between the dendrites. This liquid is rich in alloying elements and has a melting point lower than that of the base alloy. As a consequence of the applied deformation in the twin-roll caster, the solidified interdendritic material is forced back into the aluminum matrix of the strip, forming near-surface segregates. The researchers evaluated the magnitude of the near-surface microsegregation in strips having a thickness of 3.8 mm and a twin-roll cast at a speed of 1.84 m/min. Here, the value of segregate’s intrusion reached 180 microns. However, the segregation intensity and its dependence on the casting parameters were not characterized.

Several studies are known which are devoted to investigating the qualitative dependence of microsegregation formation on the twin-roll casting parameters. For twin-roll cast strips of 3xxx-series alloys, it has been established that the increase in the casting speed and/or plastic reduction in the caster leads to the appearance of an axial segregation zone. This zone is characterized by a high content of iron and magnesium [10]. This effect is related to the intense deformation and heating of the softer metal in the axial zone and the displacement of the main alloying elements in the intergranular spaces. A similar mechanism of axial segregation is observed in strips of the 6xxx-series alloys [11]. It is significant that the segregation defects in the tested strips were not eliminated during the subsequent operations of rolling and annealing. Using the example of a 5052 alloy, the influence of the casting speed [12] and the strip thickness [13] on the amount of microsegregation and mechanical properties of the strips of Al-Mg alloys were investigated. It was demonstrated that by raising the casting speed, the number of both near-surface microcracks as well as axial and intergranular segregates increases. This results in a deterioration of mechanical properties, especially strength and ductility. At the same time, a finer grain structure was observed in thinner strips. Thus, data concerning near-surface microsegregation intrusion is not yet available for high-alloyed Al-Mg-Si alloys.

The aim of the present work is to quantitative evaluate the effect of the twin-roll casting speed on the near-surface microsegregation intrusion in strips of the EN AW-6082 alloy.

Experimental procedure

To study the magnitude of intergranular microsegregation,3 mm thick and 200 mm wide strips of the EN AW-6082 alloy were twin-roll cast using a casting speed ranging from 2.32 m/min to 5.81 m/min. For the experiments, the laboratory twin-roll caster (see Figure 1) was used at the Institut für Werkstoffkunde of Leibniz Universität Hannover. The caster is described in detail in [14]. All experiments were carried out by vertically feeding the melt into the gap between the horizontally installed water-cooled rolls. The high-strength age-hardening aluminium alloy EN AW-6082 was selected for the experimental program. The chemical composition of the cast material is given in Table I.

The previously obtained optimal construction and technological parameters of the twin-roll casting process [3] were corrected by means of numerical simulations [15].This was carried out to ensure steady-state conditions of the strip's production and to prevent overloading the equipment within the selected range of casting speeds. In particular, the length of the crystallization-deformation zone was adjusted individually for each speed at a constant initial melt temperature. For the vertical melt feed from a tundish to the roll gap ceramic nozzles with cylindrical channels [3] were used. The main process parameters employed during the experiments are given in Table II.

Figure 1. Twin-roll caster used for the manufacturing the aluminium strips.

To analyze the strip's microstructure, microsections were prepared. Samples were taken and prepared from the end sections of the strips: That is, from material produced under the twin-roll casting's steady-state conditions and at stable operating temperatures. The sections were taken from a plane parallel to the twin-roll casting direction and etched with mixture of 10% solution of sulfuric acid and 5% solution of hydrofluoric acid in order to reveal secondary precipitates. A typical microstructure is depicted in Figure 2 for a strip produced using casting speed of 3.95 m/min.

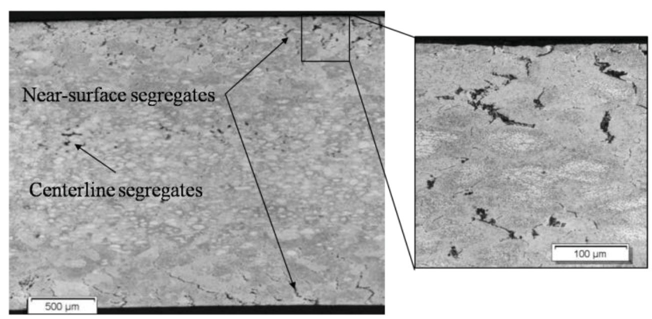


Figure 2. Etched microstructure of an EN AW-6082 alloy strip in the twin-roll casting direction, obtained using a casting speed of 3.95 m/min.

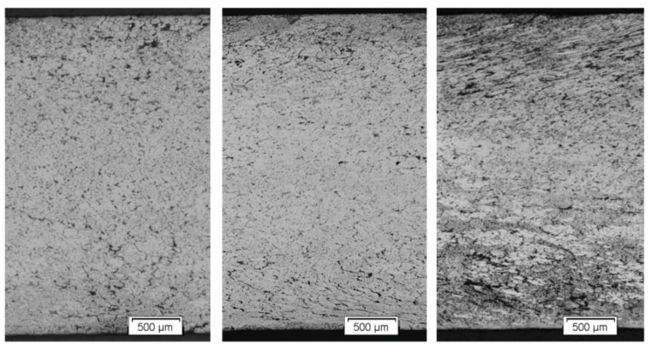
Table I. Chemical composition of the cast alloy EN AW-6082

Alloying elements	Si	Fe	Cu	Mn	Mg	Cr	Zn	Others	Al
	%	%	%	%	%	%	%	%	%
Standard demands	0.7 –1.3	max. 0.5	max. 0.1	0.4 –1.0	0.6 –1.2	max. 0.25	max. 0.2	-	balance
Analysis	1.12	0.391	0.084	0.51	0.77	0.03	0.068	0.073	96.95

Table II. Main twin-roll casting process parameters at the varied casting speeds

Initial melt temperature, °C	665	665	665	665	665
Casting speed, m/min	2.32	2.79	3.95	4.88	5.81
Crystallization-deformation zone length, mm	25	25	35	45	50
Number and size of cylindrical channels in the nozzle	2×∅6 mm	2×∅7 mm	3×∅7 mm	3×∅9 mm	4×∅8 mm
Strip thickness, mm	3	3	3	3	3
Coolant flow rate, l/min	112	112	112	112	112

The etched microsections images show areas possessing a high content of alloying elements featured as specific dark colors. The highest density of such areas is observed close to the surface of the strips in the form of microsegregation. Furthermore, for some twin-roll casting conditions centerline segregation can be detected, although these are less clear. Figure 3 shows the etched microstructure of the strips, produced using twin-roll casting speed of 2.32 m/min, 3.95 m/min and 5.81 m/min respectively. An increasing amount of near-surface segregates for elevated casting speeds is visible even without a detailed image analysis.



a b c

Figure 3. Etched microsections of the EN AW-6082 alloy strips, produced at casting speeds of 2.32 m/min (a), 3.95 m/min (b) and 5.81 m/min (c).

A quantitative evaluation of microsegregation in strips produced at different casting speeds was carried out using two techniques: By means of a digital image analysis of the micrographs and by the spectral analysis of the chemical composition distribution on the polished specimens.

For the digital image analysis, the micrographs were divided into narrow areas 50 µm high across the strip's thickness. For each of these images, the relative content of black areas was determined using Corel Photopaint®. These areas correspond to zones possessing a high content of alloying elements. Figure 4 gives an example of the thus measured microstructural fraction for a strip cast at a speed of 3.95 m/min. In the following, the depth of the black areas, averaged from the top and bottom of the micrographs, was also calculated. This quantity was chosen to characterize the near-surface microsegregation level.

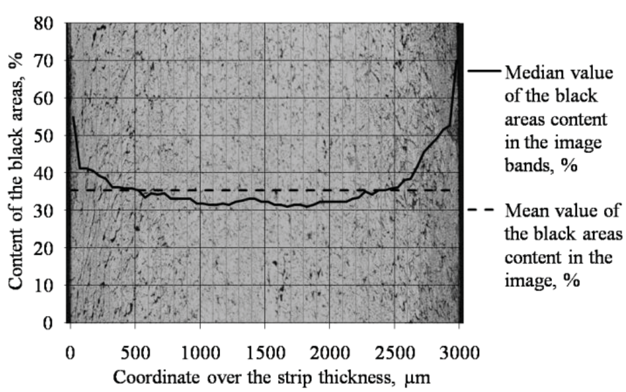


Figure 4. Distribution of the black regions across the strip's thickness in the microsection image of a strip produced using a casting speed of 3.95 m/min.

To verify the results obtained by means of the described metallographic analysis of thin sections, a chemical element analysis was performed by means of an electron probe microanalyzer (EPMA). For this purpose, the etched sample was stepwise fine polished finally using a 1 µm diamond paste. The measurements were carried out on a JEOL JXA-8900R using an acceleration voltage of 20 kV and a sample current of $2 \cdot 10^{-8}$ A. For each section, the distribution of aluminum and the alloying elements across the thickness of the strip was obtained. The thickness of near-surface zones was then measured, in which the distribution of the alloying elements' content substantially differs from the average values across the strip's thickness. An example of such a measurement for a strip produced with a casting speed of 3.95 m/min is shown in Figure 5.

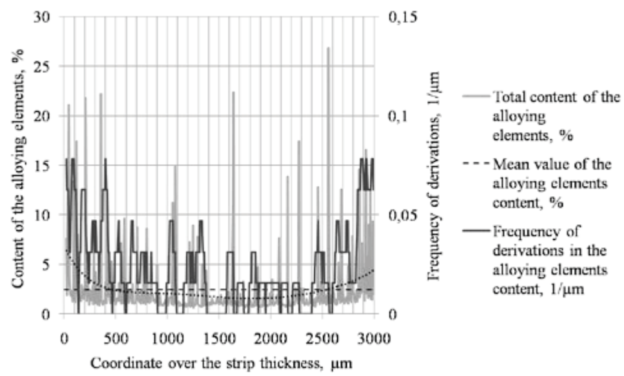


Figure 5. Distribution of chemical elements across the thickness of a strip, produced at a casting speed of 3.95 m/min, obtained by means of EPMA using line-scanning.

Results

The values of near-surface expansion of microsegregation into the central layers of the strips were obtained by the two methods for five different casting speeds. The established dependence of microsegregation intrusion-depth on the twin-roll casting speed is shown in Figure 6.

Discussion

The microsegregation magnitudes obtained by the two different methods showed a high correlation. The differences in the results do not exceed 10 %. This correlation suggests the possibility of applying each of the methods to evaluate the microsegregation magnitude. The curves' shape in Figure 6 shows that the microsegregation depth increases on elevating the casting speed. This correlates well with the known data [9, 12, 13]. The dependence of the microsegregation depth on the casting speed is approximately linear and exhibits no extremes within the considered casting speed range. This confirms the mechanism of segregate formation proposed in [9], in which the shape of solidus isothermal is seen the main influencing factor. At the same time, the shape of the solidifying interface directly depends on the casting speed. Thus, for twin-roll casting at 3.95 m/min near-surface microsegregation intrusion was, on average, 570 µm for the two sides of the strip. This amounts to 38% of its total thickness. At 2.32 m/min casting speed, microsegregation in the strip's microsections only exist close to the strip's surface and do not exceed 20% of the total strip's thickness.

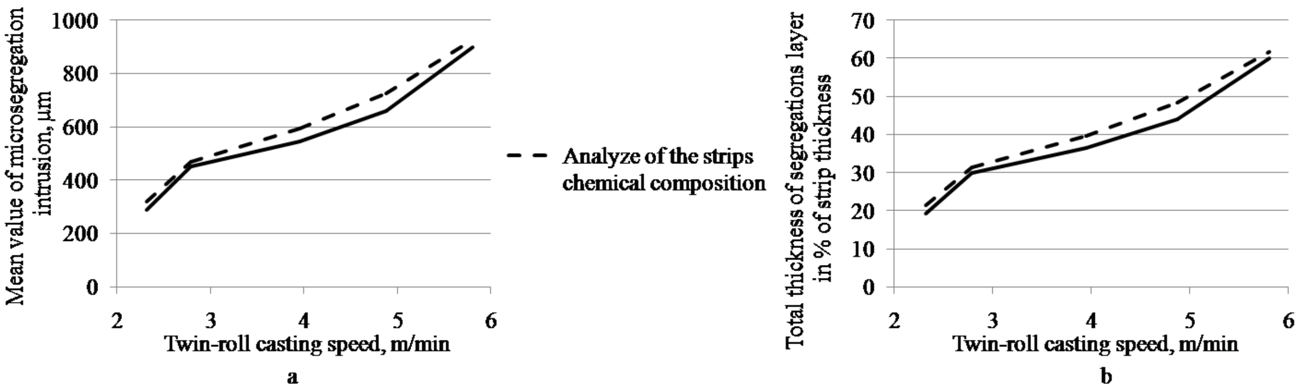


Figure 6. Dependence of near-surface microsegregation intrusion on the casting speed of the EN AW-6082 alloy strips in absolute value (a) and relative to the strip thickness (b).

However, when the casting speed is increased by a factor of 2.5 to 5.81 m/min, the total microsegregation intrusion-depth for the two sides reaches 60.8% of the strip's thickness. Those strips possessing such inhomogeneous microstructures require an additional treatment to meet the standard requirements owing to their poor mechanical properties. For this purpose, a homogenization heat treatment can be applied. Furthermore, microsegregations can be reduced by higher recrystallization rates due to plastic deformation in the twin-roll caster or during subsequent hot metal forming processes.

Conclusions

As a result of the experimental studies on the twin-roll casting of the EN AW-6082 alloy strips and an analysis of their microsections, a quantitative dependence of the near-surface microsegregation intrusion-depth on the casting speed was obtained. A characterization of the microsegregation level in the strips was carried out by digital image analysis of the micrographs and by means of EPMA using line scanning chemical element analysis. It was established that by increasing the casting speed through a range from 2.32 m/min to 5.81 m/min, the near-surface microsegregation intrusion increases from 305 µm to 913 µm for each side of the strip cross-section. This amounts to 20.3% and 60.8% of the total strip thickness, respectively. The dependence of the growth in the microsegregation layer's thickness on the strip casting speed is approximately linear. Thus, at a twin-roll casting speed of over 5.3 m/min prevailing segregated layers can be observed in the thin strips. It can be supposed, that with a further increase in casting speed a more homogeneous strip microstructure across its thickness could be achieved.

Acknowledgements

The authors would like to thank the Federal Ministry of Education and Research of Germany (BMBF) and Ministry of Education and Science of Ukraine for their financial support of the international cooperative scientific work carried out within the scope of the project 01DK12032.

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