TWIN ROLL CASTING and MELT CONDITIONED TWIN-ROLL CASTING OF MAGNESIUM ALLOYS

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Abstract. Recently, BCAST at Brunel University has developed a MCAST (melt conditioning by advanced shear technology) process for conditioning liquid metal at temperature either above or bellow the alloy liquidus using a high shear twin-screw mechanism. The MCAST process has now been combined with the twin roll casting (TRC) process to form an innovative technology, namely, the melt conditioned twin roll casting (MC-TRC) process for casting Al-alloy and Mg-alloy strips. During the MC-TRC process, liquid alloy with a specified temperature is continuously fed into the MCAST machine. By intensive shearing under the high shear rate and high intensity of turbulence, the liquid is transformed into conditioned melt with uniform temperature and composition throughout the whole volume. The conditioned melt is then fed continuously into the twin-roll caster for strip production. The experimental results show that the AZ91D MC-TRC strips with different thicknesses have fine and uniform microstructure. The strip consists of equiaxed grains with a mean size of 60-70μm. The strip displays extremely uniform grain size and composition throughout the whole cross-section. Investigation also shows that both TRC and MC-TRC processes with reduced deformation are effective to reduce the formation of defects, particularly the formation of the central line segregations.

1. Introduction

It is difficult for Mg alloys to undergo solid state deformation to fabricate strips at room temperature. In the conventional process, Mg-based alloy strips are fabricated by hot-rolling slabs prepared by direct chill (DC) casting. As the slabs are coarse-grained materials, a sophisticated rolling process has to be carried out carefully to fabricate much thinner strips [1-5]. These repeated steps result in low production efficiency and high production cost. To overcome the difficulties associated with solid state deformation process, a twin roll casting (TRC) process has been developed to produce Mg alloy strips directly from liquid Mg alloys [3-8]. In the recent years, TRC technique has been developed extensively and lots of research work has also been carried out to improve our understanding of the solidification mechanism of TRC process [4-7]. The conventional TRC process integrates casting and rolling into a single process [8-11] and particularly stresses the large deformation in the hot-rolling process. The major problems with the conventional TRC process are coarse columnar grains of a size of approaching 1mm, severe chemical segregation at the centre of the strip, large amounts of defects like bleeding and only casting dilute alloys with narrow freezing range. Most of such problems are created during the deformation process [11-13]. The conventional TRC process involves a substantial amount of force to weld the two pre-solidified shells in the bite of the two rolls. As a consequence of this large force, the solute-rich liquid is squeezed between the growing dendrite, resulting in severe central line segregation and casting defects else. It is more reasonable to consider that TRC is a casting process, and that high quality strip can be produced by relying on the control of the solidification process rather than relying on the deformation process. Based on the above consideration, a twin roll caster with adjustable load was designed and attached to a MCAST (melt conditioning by advanced shear technology) processor for fabricating Mg alloy strips.

The MC-TRC process combines the advantage and function of both the MCAST process and the TRC process. The key technology in the MC-TRC process is the MCAST process developed in BCAST [14-16]. The MCAST equipment has a pair of co-rotating, fully intermeshing and selfwiping screws rotating inside a barrel with accurate temperature control. The screws have specially designed profiles to achieve high shear rate, high intensity of turbulence and the desirable residence time, which ensures the uniform temperature, the uniform composition and the homogeneous transfer of heat in the whole volume of liquid melt. Normally, in the MC-TRC process, liquid alloy is continuously fed into the MCAST machine, where the liquid alloy is intensively sheared for a specified period of time. The sheared liquid alloy is then fed continuously into the twin roll caster for trip casting. In this paper, we report our successful preparation of AZ91D Mg alloy strips by both TRC and MC-TRC processes. The microstructure, grain size, compositional variation of the strips was investigated in detail. The understanding in the nucleation and growth of the grains in the MC-TRC processes and the new design of twin-roll caster is beneficial to develop advanced materials and new production technology, and to fabricate high quality Mg- and Al-based alloy strips in the near future.

2. Experimental procedure

The twin-roll caster used in this research was a small lab-scale version of TRC machine with a pair of opposed steel rolls 318 mm in diameter and 350 mm in width. The rolls with inner water-cooled system have a maximum speed of 40rpm. Some core parameters including roll speed, setback, roller gap and strip thickness can be adjusted, even while a cast is in progress. Under the protection of a N_2 + 0.5 vol % SF_6 gas mixture, magnesium AZ91D alloy ingots were melted, and transferred into the preheated header-boxes for twin roll casting.

The MCAST machine was attached to the twin roll caster. The preparation, melting and protection of AZ91D Mg alloys has described in the TRC process. The liquid melt with a specified temperature is fed continuously into the twin screw melt conditioning devices [16] under the protection of a N_2 + 0.5 vol % SF_6 gas mixture. The conditioning devices are operated and the melt is sheared at the maximum rotation rate of 1000 rpm. The shearing time is also controlled in the range of ~60s. The sheared liquid was fed steadily into the twin roll caster and forms strips with different thicknesses dependent on the roller gap.

Samples cut from both TRC and MC-TRC AZ91D Mg alloy strips were ground, polished carefully and etched in a 0.5% nitride solution. The microstructure was examined using an optical microscope equipped with an image analysis system. Further details were investigated by scanning electron microscopy (SEM) with an attached X-ray energy-dispersive spectroscope (EDS). Throughout the whole samples fabricated by both TRC and MC-TRC processes, the variation of composition, grain size and microstructure were also studied.

3. Results

Figure 1 (a) shows the microstructure on the entire cross-section of the TRC strip in the longitudinal direction. Little segregations, such as central line segregations, were observed in the strips. Figures 1(b)-(d) present more details of the microstructure. From the top to the bottom in the strip, the strip has three layers (shown in Fig. 1(a)), namely, the top layer, the central layer and the bottom layer. On the surface of the strip, there is a thin layer which consists of fine grains (shown in Fig. 1(b)), and is called the outer chill zone. Following the chill zone, a columnar zone which consists of coarse dendrites is developed. In this zone, the microstructure varies significantly. Some dendrites are able to grow up to 1300-1500μm (shown in Fig. 1(c)). Next to the columnar zones, a central zone that consists of large amounts of equiaxed grains is presented (shown in Fig. 1(d)). The central region of the strip always has a markedly different structure. One can notice that the central region have a brighter contract than other zones (shown in Fig. 1(a)), suggesting that the composition in this zone is completely different with that of other zones. To quantify the grain size in the different locations, the variation of grain size through the thickness in the samples was investigated. The result was shown in Fig. 2. The size of grains is smaller (about 220 μm) in the chill zone. However, in the column zone, with increasing the thickness, the grain sizes rise sharply and have a mean size of 550~750μm dependent on the distance. With further increasing the distance

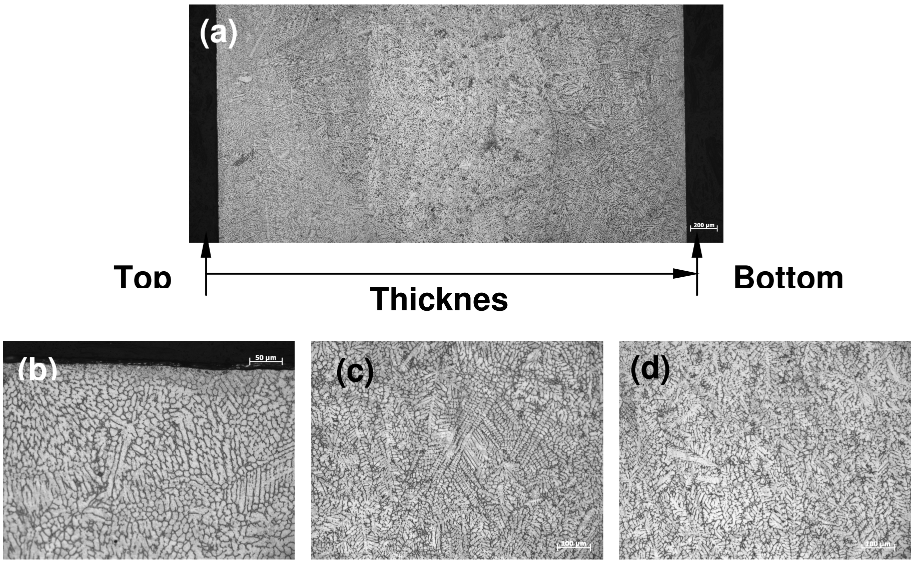

Fig. 1 (a) Microstructure of the entire cross-section of magnesium AZ91D TRC strips at longitudinal direction, and microstructure of (a) the bottom surface (chill zone), (c) the bottom region (column zone) showing columnar dendrites and (d) the central region showing the equiaxed grains.

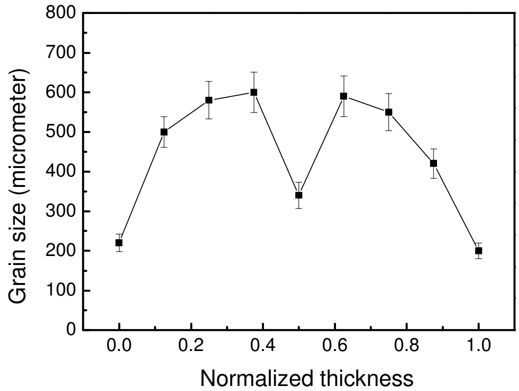

Fig. 2 Grain size variation with increasing thickness in the 4mm thick AZ91D alloy strips produced by TRC process.

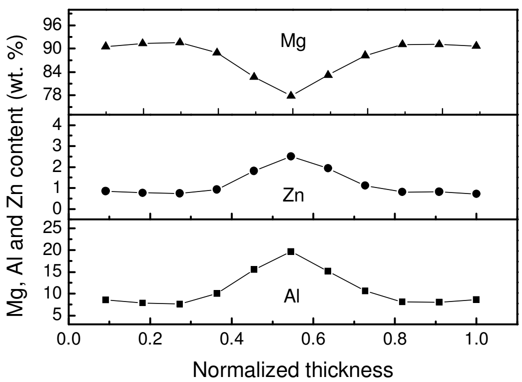

Fig. 3 Chemical composition variation (Mg, Al and Zn) with increasing thickness in the 4mm thick AZ91D alloy strips produced by TRC process.

into the central zone (equiaxed grain zone), the grain size reduce significantly to 300μm. In the top layer, the variation of grain size is similar to that of the bottom layer.

The composition variation throughout the entire TRC strips was also investigated. Along the thickness direction from the top surface to the bottom surface, the content variation (wt %) of Mg, Al and Zn elements with increasing the distance were shown in Fig. 3. With increasing the distance, Al and Zn contents have no obvious variation. But, at the central region, both Al and Zn contents start to change and increase sharply. Al content reach to nearly 20% and Zn content is up to 3%. This result suggests severe central line segregation in the as cast strip. With further increasing the thickness from the centre to the bottom surface, both Al and Zn content reduce, which has the same variation with that from the centre to the top.

Figure 4 (a) shows the entire cross-section microstructure of the MC-TRC strips with a thickness of 4mm in the longitudinal direction. No macro-segregations were observed throughout the entire samples. To check the size, morphology and distribution of solid phases, different locations

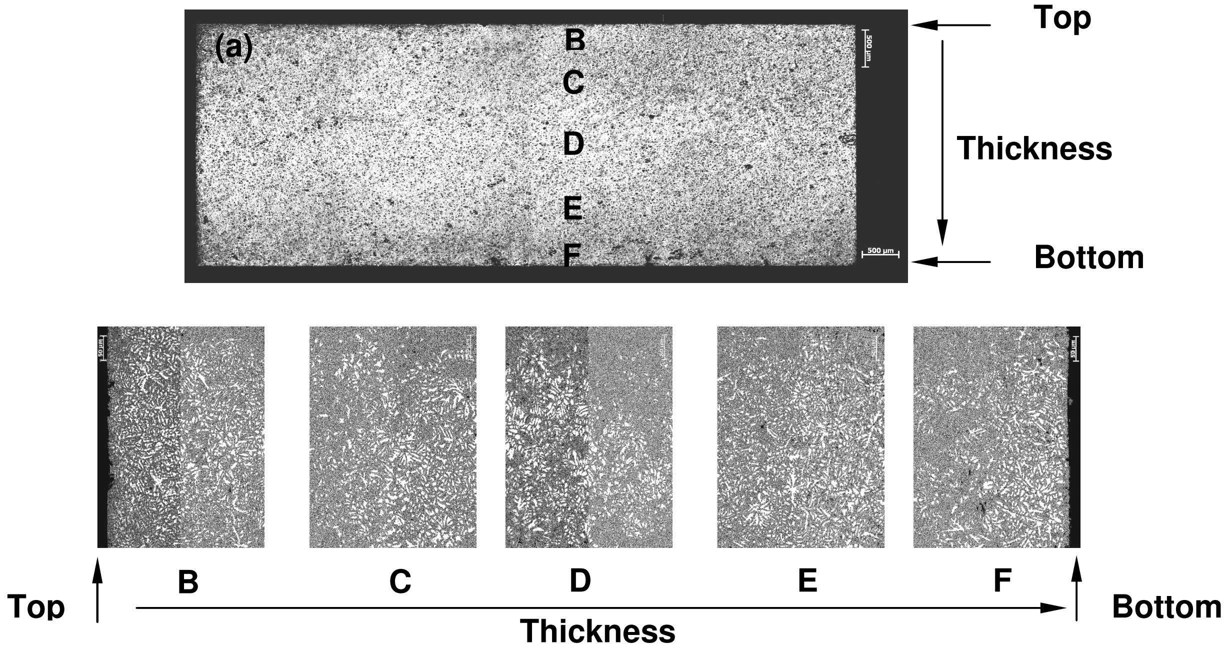

Fig. 4 (a) Microstructure of the entire cross-section of magnesium AZ91 MC-TRC strips at longitudinal direction, B-F microstructural variation throughout the whole thickness direction from the top to the bottom showing the extremely uniform structure.

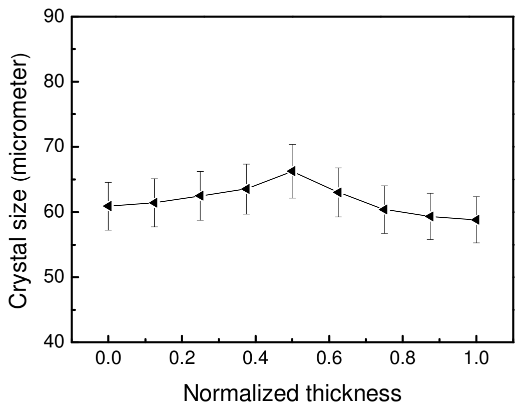

Fig. 5 Grain size variation with increasing thickness in the 4mm thick AZ91D alloy strips produced by MC-TRC process.

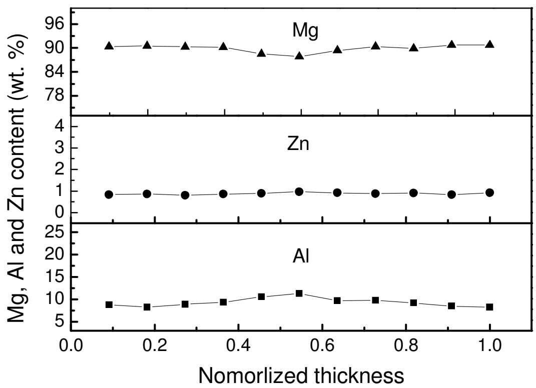

Fig. 6 Chemical composition variation (Mg, Al and Zn) with increasing thickness in the 4mm thick AZ91D alloy strips produced by MC-TRC process.

throughout the thickness direction (shown in Fig. 4(a)) in the strip were chosen and their microstructures were shown in Figs. 4 B-F. It is important to point out that no columnar dendrites were seen in all locations. Throughout the entire cross-sections, only equiaxed grains with uniform size were observed. The mean size of grains throughout the thickness in the MC-TRC strip was investigated in detail and shown in Fig. 5. The size of equiaxed grains is extremely uniform. Compared with the grain sizes of TRC strip, the mean size of the equiaxed grains in the MC-TRC strip is only one tenth of the mean size of the dendrites in the TRC samples. On the other hand, in the MC-TRC strip, the morphology and size of grains are really uniform, but in the TRC strip, the morphology and size of dendrites vary significantly and have different morphologies and sizes in the different locations. The significant reduction of the grain sizes and the extreme uniformity of the morphology are caused by the advanced MC-TRC process, and are beneficial to improve both strength and ductility of the strips. The composition variation throughout the thickness direction of the MC-TRC strip was also investigated. From the top to the bottom, with increasing the thickness, the content variation (wt %) of Mg, Al and Zn elements were shown in Fig. 6. With increasing the thickness, Al, Mg and Zn contents have no obvious change. This result suggests that there is no obvious central line segregation in the MC-TRC strip.

4. Discussion

During TRC casting, the microstructure of TRC strips depends significantly on the solidification behaviour of the liquid melt in the sump [8]. As the nucleation initiates from the roller surface, temperature gradient between the roller surface and the liquid melt causes the formation of dendrites easily. Some grains with the most favourably crystallographic orientation are able to grow and form the columnar dendrites. Under the above solidification conditions, the dendritic growth always results in enriched liquid in the growth front of solidification. As the casting proceeds and both the solidified shells approach the roll bite, their dendritic networks and residual liquid melts interact and combine to form the final solidified strips. In the conventional TRC process, during the hot-rolling process, the deformation caused by drastically compressive action is so strong that the enriched liquid is squeezed into any channels to form defects such as macro-segregations and bleedings. These defects reduce mechanical properties and degrade the strip quality. However, in our new TRC process with a small force, the enriched liquid only subject to a reduced level of deformation. Therefore, the enriched liquid is not squeezed strongly and prevents effectively the form of large amounts of macro-segregation. From the observation of microstructure and defects (shown in the Fig. 1(a)), only little defects can be found in the strip fabricated by using the new TRC process. This means that the TRC technology with a reduced force is effective to prevent the formation of defects. By making a comparison with the Mg-alloy strips produced by the conventional TRC equipment with stronger deformation, the new TRC equipment produces AZ91D strips with much less segregations even than the AZ31 strip produced by the conventional TRC equipment [7]. It is well-known that AZ91D is much more prone to segregation than AZ31. As a consequence of reduced force, the new TRC equipment is much smaller and more compact, and of course cost less compared with the conventional TRC equipment.

For MC-TRC process, the nucleation and growth of grains is completely different with that of the TRC process. The solidification behaviour of sheared liquid melt has been discussed by Fan et al [14-16]. According to the classical theory of nucleation [2], when overheated liquid melt is poured into the relatively cold mould, heterogeneous nucleation takes place immediately in the undercooled liquid close to the mould wall. The majority of the nuclei are transferred to the overheated liquid region and dissolved, so only a small proportion as low as 0.3% of nuclei survive and contribute to the final microstructure, resulting in a coarse and non-uniform microstructure. This has been observed in the TRC strips that consist of columnar dendrites, shown in Fig. 1. In the MC-TRC process, the fluid flow inside the barrel of MC-TRC machine is characterised by high shear and high intensity of turbulence. A direct consequence of such melt flow characteristics is that the melt inside the barrel of the MC-TRC machine has a uniform temperature, uniform chemical composition and fast heat removal rate. Such conditions will ensure a 100% nuclei survival rate. Perhaps more importantly, intensive melt shearing will convert the oxide particle clusters and oxide films usually present in the liquid metal into fine, almost mono-sized and well-dispersed particles, which are completely wetted by the liquid metal under the shear force. According to the free growth theory [17-18], once a critical undercooling corresponding to the oxide particle size is reached, heterogeneous nucleation will occur throughout the entire volume of the conditioned liquid metal [15-16]. Due to the uniform temperature and composition of the liquid metal, all the nuclei created will survive and grow without preferential orientation [16]. Moreover, higher cooling rates provided by the rotating roller with inner water-cooled system can also increase the thermal undercooling for nucleation and hence increasing the nucleation rate. All these factors will promote a fine and fully equiaxed microstructure [19] in the entire cross section of the strip. Hence, the intensive forced convection provided by the MCAST machine has in the first time eliminated successfully both the columnar grains and the macro-segregation in the as cast strip.

5. Summary

Magnesium AZ91D strips with high quality were fabricated successfully by TRC and MC-TRC processes. Microstructure, chemical composition and grain size of the strips were investigated in detail. Throughout the entire MC-TRC strip, extremely uniform composition and grains were achieved. The mean grain size of the MC-TRC strip is about 60μm, which is one order of magnitude smaller compared with that of the TRC strip. This originates from uniform composition and temperature field throughout the whole volume of liquid melt as well as the well-dispersed heterogeneous nucleation sites provided by the intensive shearing in the MCAST machine. Investigation also shows that both TRC and MC-TRC strips show little central line segregation, suggesting that both TRC and MC-TRC processes with reduced deformation are effective to prevent the formation of segregations.

References

[1] P. Juchmann, S. Woff, Proc. 59th Annual World Magnesium Conf., Int. Magnesium Association, Montreal, Canada, 2002, p. 49.
[2] F. W. Bach, S. Schacht, A. Rossberg, Continuous Casting, ed. by H. R. Mueller (Weinhim, Germany, Wiley-Vch 2006), p. 94.
[3] D. Liang, C. B. Cowley, JOM, May 2004, p. 26.
[4] R. V. Allen, D. R. East, T. J. Johnson, W. E. Borbidge, D. Liang, Magnesium Technology 2001, ed. J. Hryn, TMS 2001, p. 75.
[5] S. S. Park, J. G. Lee, H. C. Lee, N. J. Kim, Magnesium Technology 2004, ed. A. A. Luo, TMS 2004, p. 107.
[6] L. Loechte, H. Westengen, J Rodseth, Magnesium Technology 2005, ed. N. R. Neelameggham, TMS 2005, p. 247.
[7] I. H. Jung, W. Bang, I. J. Kim, W. J. Park, D. Choo, S. Ahn, Magnesium Technology 2007, ed. R. S. Beals, TMS 2007, p. 85.
[8] Direct strip casting of metals and alloys, ed. M. Ferry (Cambridge, England, Woodhead publishing 2006), p. 100-150.
[9] Ch. Gras, M. Meredith, J. D. Hunt, J. Mater. Proc. Tech. 167(2005), p. 62.
[10] Ch. Gras, M. Meredith, K. Gatenby, J. D. Hunt, Mater. Sci. Forum 396-402 (2002), p. 89
[11] M. Yun, S. Lokyer, J, D. Hunt, Mater. Sci. Eng. A 280 (2000), p. 116.
[12] S. A. Lockyer, M. Yun, J. D. Hunt, D. V. Edmonds, Mater. Characterization 37 (1996), p. 301.
[13] B. Forbord, B. Andersson, F. Ingvaldsen, *et al.*, Mater. Sci. Eng. A 415 (2006), p. 12.
[14] Z. Fan, Inter. Mater. Rev. 47 (2002), p. 49.
[15] Z. Fan, G. Liu, Y. Wang, J. Mater. Sci. 41 (2006), p. 3631.
[16] Z. Fan and G. Liu, Acta Mater., 53 (2005), p. 4345.
[17] G. P. Ivantsov, Dokl, Akd. Nauk SSSR 58 (1947), p. 567.
[18] A. Barbieri, J. S. Langer, Phys. Rev. A39 (1989), p. 5314.
[19] M. T. Rappaz, Ph. Acta Met. 35 (1987), p. 1487.