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Microstructure control during twin roll casting of an AZ31 magnesium alloy

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Abstract. The existing twin roll casting technique for magnesium alloys suffers heterogeneity in both microstructure and chemistry and downstream processing is required to improve the strip quality, resulting in cost rise. In the present work, twin roll casting was carried out using an AZ31 magnesium alloy, with the application of intensive shearing melt conditioning prior to casting. The effect of process parameters such as pouring temperature and casting speed on microstructure control during casting and subsequent downstream processing was studied. Experimental results showed that the melt conditioning treatment allowed the production of AZ31 strips with uniform and refined microstructure free of centreline segregations. It was also shown that an optimized combination of pouring temperature and casting speed, in conjunction with a strip thickness control operation, resulted in uniformly distributed stored energies due to enhanced plastic deformation, which promoted recrystallization during casting and subsequent heat treatment. Strips prepared by twin roll casting and homogenization developed similar microstructural features to those prepared by twin roll casting followed by lengthy downstream processing by homogenization, hot rolling and annealing and displayed a weaker basal texture, exhibiting a potentially better formability.

1. Introduction

Magnesium alloys are the lightest structural material with high specific strength and their sheets represent a universal semi-finished product group for ultra light and rigid sheet forming for automotive structures and electronic devices. Stamping of magnesium alloy parts from sheet products provides additional design freedom to achieve intricate cuts and various shapes with tight tolerance requirement. However, due to limited ductility, magnesium sheets produced via conventional slab casting and thermo-mechanical processing are expensive and lack cutting edges in competing with cast magnesium products and other structural materials such as aluminium, steel and plastic composites. Large scale applications of magnesium sheets require a breakthrough in their production technology. Twin roll casting (TRC) has demonstrated a potential to produce magnesium strips at significantly reduced cost with an improved microstructure due to the higher cooling rate compared with conventional ingot casting [1]. However, the quality of the magnesium alloy strips produced by the existing TRC technique is limited by the formation of coarse columnar dendrite grains and centreline segregation [1, 2]. A common approach to overcome these limitations is to produce strips much thicker than the required final gauge and thus further mechanical processing can be done to

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improve the microstructure and eliminate the chemical heterogeneity [3, 4]. As a result, the overall cost is increased and the products become less competitive.

In order to fully take advantage of the TRC process, it is critical to obtain a uniform and refined microstructure, homogeneous chemistry and significantly improved mechanical properties. The present work was carried out to investigate the effect of casting parameters on the microstructure development during a melt conditioned twin roll casting and the subsequent downstream processing.

2. Experimental details

A commercial AZ31 magnesium alloy (Mg-3.34Al-0.97Zn-0.31Mn, wt%) was supplied by Magnesium Elektron (Manchester, UK) and was used in this investigation. The alloy was melted in 10 kg batches in a steel crucible at 670°C under a protective atmosphere. The alloy melt was then transferred to a twin screw melt conditioning unit and subjected to intensive shearing at ~ 645°C for 60 s. The screw rotation speed was ~ 600 rpm, giving a melt shear rate of ~1633 s^{-1} [5]. The conditioned melt was immediately fed into a vertical twin roll caster (ϕ100×100) or a horizontal one (ϕ318×150) under a protective atmosphere. The strip thickness was controlled in the range of 1.5 – 6mm and the casting speed was between 1 – 5 m/min. Downstream processing was carried out on some selected as-cast strips by homogenization, hot rolling, and annealing.

Specimens for microstructure and texture characterization were cut from the middle of a strip along the casting/rolling direction and all examinations were carried out on the longitudinal transverse plane unless stated. Specimens for optical microscopy were prepared using standard metallographic procedures followed by etching in a solution of 5% HNO_3 in ethanol. An acetic-picral acid colour etching solution comprising of 4.2g picric acid, 70ml ethanol, and 15ml distilled water and 15ml acetic acid was employed for preparation of samples to be examined under polarized light. Electro-polishing at 12V in a solution of 15% nitric acid in ethanol at -30°C for 30s was carried out to prepare surfaces for scanning electron microscopy (SEM) and electron backscatter diffraction (EBSD). The optical microscopic observations and analyses were performed on a Carl Zeiss AXioskop 2MAT optical microscopy equipped with image processing software. SEM imaging and EBSD mapping were carried out on a Zeiss Supera35 FEGSEM equipped with an Oxford Instruments EBSD system.

3. Results and discussions

3.1 The effect of melt conditioning

Figure 1 shows a typical microstructure for the AZ31 strips produced by melt conditioned twin roll casting. It can be seen that, apart from a negligible thin chill fine grained surface layer, the micro-

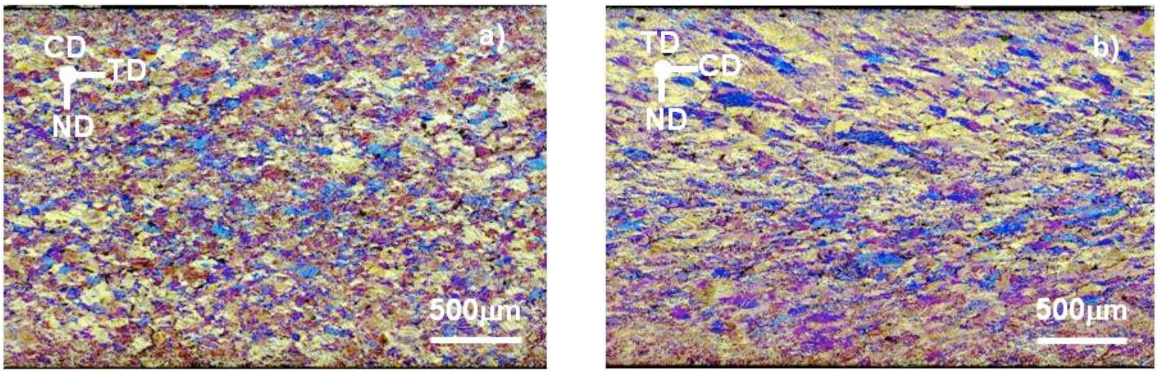

Figure 1. Optical micrographs of the as-cast microstructure obtained at a pouring temperature of 640°C and casting speed of 2.4m/min: a) ND-TD plane; b) CD-ND plane, where CD denotes the casting direction, TD the longitudinal transverse direction and ND the normal direction.

structure throughout the strip thickness is uniform, although grains are elongated viewing from the TD plane (figure 1b) due to plastic deformation along the casting direction. It should be noted that the microstructure as shown in figure 1 is significantly finer than that for the same alloy strips produced by normal twin roll casting without melt conditioning [6]. More importantly, the microstructure is free from macro-scale centreline segregations, which occur in normal twin roll casting due to directional crystal growth. It has been demonstrated that under an intensive shear stress-shear strain field, the alloy melt develops uniform temperature, uniform chemical composition and evenly dispersed nucleation agents, and therefore, nucleation takes place throughout the entire volume of the liquid, giving rise to a refined and uniform microstructure [7]. The uniform microstructure obtained in the present investigation suggests that heterogeneous nucleation took place evenly from surface to centre in the solidification zone and that the nuclei formed survived at the same rate throughout the solidification volume, growing into spherical crystallites. This solidification process prevented the accumulation of solute concentrated liquid in the centre region from occurring and effectively eliminated the formation of centreline segregations.

3.2. The effect of casting parameters

The experimental results showed that, although the application of melt conditioning by intensive shearing prior to casting was essential for achieving a uniform microstructure and homogeneous chemistry, an optimized combination of casting parameters was also important for achieving the desired microstructure and texture during casting and the subsequent downstream processing.

3.2.1 Casting speed The effect of casting speed on the performance of twin roll casting has been widely studied for steel, aluminum alloys and magnesium alloys as well [1, 3]. The present study focused on microstructural responses to the change of casting speed and their impact on the downstream processing. Figure 2 shows microstructures for strips obtained at two different casting speeds. It can be seen that the microstructure obtained at 4.9m/min is primarily characterized by dendritic networks (figure 2a), whereas the structure obtained at the reduced speed of 2.4m/min has totally different features (figure 2b). It was found that plastic deformation contributed more to the microstructural evolution with decreasing casting speed and at a certain combination of casting speed and pouring temperature the microstructure was dominated by deformation features such as shear bands, deformation bands and twins as shown in figure 2b. In many cases, groups of fine and equiaxed grains were observed due to dynamic recrystallization. As casting speed decreases, the melt in the solidification will have longer time to release heat away through the roll surfaces and the solidified strip. The mushy zone depth is expected to be reduced together with a lowered temperature at the roll nip, the strip exiting point. As a result, deformation zone is lengthened and the amount of plastic

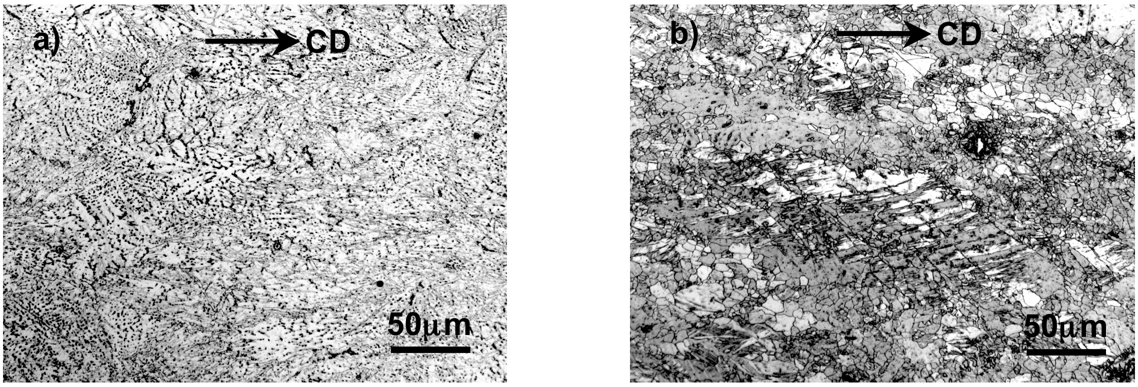

Figure 2. Optical micrographs showing microstructures obtained at a pouring temperature of 640°C and a casting speed of a) 4.9m/min and b) 2.4m/min.

deformation increases if the gauge thickness and the setback length remain constant. In the present study, the enhanced stored energy in the material was found to promote recrystallization during the subsequent homogenization. As expected, the microstructures in figure 2 exhibited different performances during homogenization. Figure 3 shows the corresponding microstructures after homogenization at 400°C for 1h. Although recrystallization completed in both structures, the strip produced at the lower speed developed a truly uniform, fine grain structure, with an average grain size of about 10μm, while the strip obtained at the higher speed could only develop a heterogeneous grain structure, dominated by large and irregular grains.

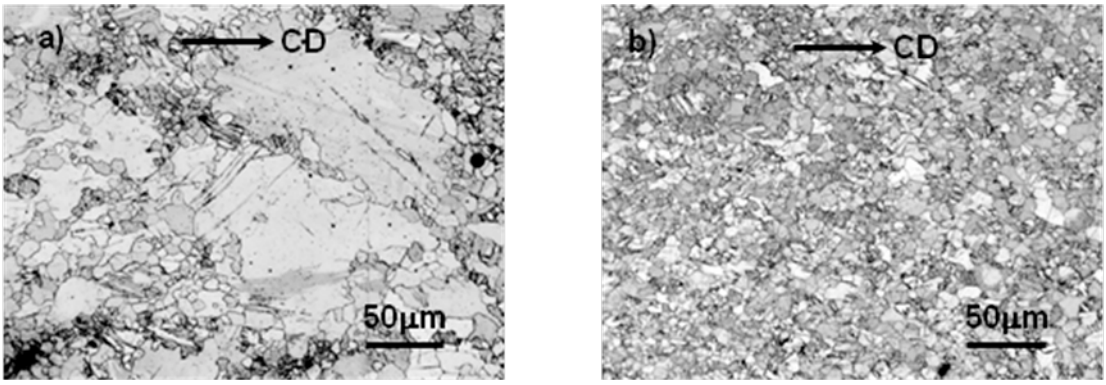

Figure 3. Optical micrographs showing microstructures homogenized at 400°C for 1h for samples prepared at a pouring temperature of 640°C and a casting speed of a) 4.9m/min and b) 2.4m/min.

3.2.2. Pouring temperature Reducing pouring temperature was found to have a similar effect as decreasing casting speed on microstructure development. Figure 4 shows the as-cast microstructure at two different pouring temperatures. A decrease of 12°C in pouring temperature caused a substantial change in the characteristic features of the microstructure. It can be seen from figure 4 that the microstructure obtained at 650°C is dominated by an equiaxed dendritic network, although features of plastic deformation such as deformation bands and twins are visible, whereas the microstructure obtained at 638°C displayed a dynamic restoration dominated features as the characteristic dendritic network was destroyed and a significant number of new grains formed due to dynamic recrystallization. Lowering pouring temperature was considered to have reduced the temperature gradient from the roll surface to the solidification centre and promoted uniform heterogeneous through the gauge thickness. Again, the mushy zone depth was reduced as less cooling was required, giving

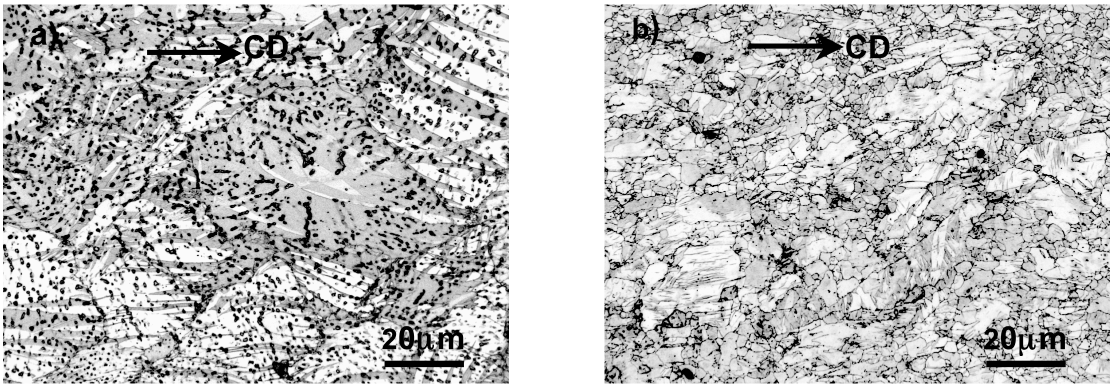

Figure 4. Optical micrographs showing as-cast microstructures obtained a casting speed of 3.1m/min and a pouring temperature of a) 650°C and b) 638°C.

rise to enhanced plastic deformation.

3.3. The effect of plastic deformation

During TRC, plastic deformation takes place immediately after solidification, resulting in the healing of casting defects such as internal shrinkages and porosities. Plastic deformation has also benefits in improving surface quality, generating new grain boundaries and refining eutectic/dendrite structure and second-phase particles. More importantly, plastic deformation generates stored energies in the material, which can trigger dynamic recrystallization during TRC and promote recrystallization during heat treatment. This is of particular importance as the provision of sufficient stored energy can lead to the formation of a fully recrystallized microstructure upon subsequent heat treatment. Consequently, further mechanical processing by hot rolling is required only for precise control of strip thickness and shape and the processing intensity will be significantly reduced. Figure 5a shows a homogenized microstructure for a strip sample prepared with controlled deformation, in comparison with that for a sample undergone a lengthy downstream processing (figure 5b). Both microstructures show surprisingly similar features in terms of grain size and distribution, twin populations and second-phase particles size and distribution. EBSD measurements showed that both samples had similar texture,

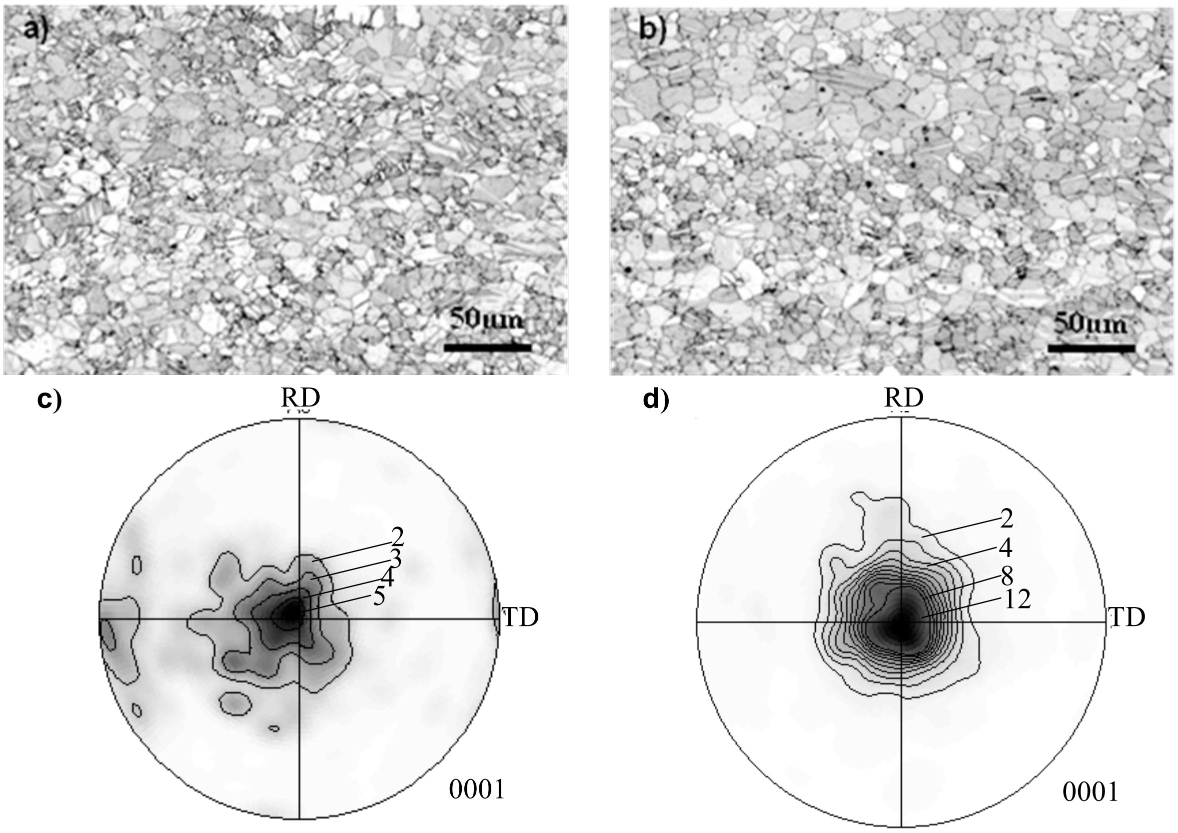

Figure 5. Optical micrographs showing microstructures for samples a) cast at 640°C, 2.4m/min and homogenized at 400°C for 1h (thickness = 2.5mm), b) cast at 640°C, 1.35m/min (6mm), homogenized at 400°C for 1h and hot rolled at 400°C to 73% (1.6mm) and annealed at 350°C for 2 h; and (0001) pole figures c) and d) showing the corresponding textures of microstructures a) and b) respectively (figures show texture intensity times random) –RD denotes rolling direction, which is identical to the casting direction (CD) in this study.

dominated by the basal component (figure 5c and d). However, the intensity of the dominating basal texture for the homogenization-only sample was significantly weaker than that for the sample subjected to a downstream processing by homogenization, hot rolling, and annealing. A weaker texture is normally related to better formability for magnesium alloys. The above result suggests that the elimination of hot rolling and the related reheating and annealing procedures has a positive effect on the improvement of formability for the material without compromise in strength.

While insufficient plastic deformation may lead to a prolonged annealing for completing recrystallization an excessive amount of plastic deformation will have some negative effects such as higher separation force and thus increased machine capacity requirement, decreased casting speed and possibly more intensified textures, etc. Besides, the amount of plastic deformation determines the time required to complete recrystallization at a given temperature during heat treatment, which must match well the time for the completion of solute homogenization in order to prevent microstructure from extensive coarsening. Therefore, plastic deformation needs to be controlled and optimized to achieve the best result in terms of process design, operation, and microstructure development.

4. Summaries

Twin roll casting experiments have been carried out for an AZ31 wrought magnesium alloy, with the help of intensive shearing melt conditioning prior to casting, and the effect of pouring temperature and casting speed was investigated. The employment of melt conditioning resulted in the production of AZ31 strips of a refined and uniform microstructure and homogeneous chemistry. An optimized combination of casting parameters, in conjunction with thickness control operation, made it possible to strictly control the microstructure during casting and heat treatment and to obtain a required microstructure with improved properties and potentially limited further mechanical processing.

Acknowledgement

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