Materials Chemistry and Physics 116 (2009) 11–15

Contents lists available at ScienceDirect

Materials Chemistry and Physics

journal homepage: www.elsevier.com/locate/matchemphys

Materials science communication

Microstructure and texture of twin-roll cast Mg–3Al–1Zn–0.2Mn magnesium alloy

N. Tang [a], M.P. Wang [a], H.F. Lou [a], Y.Y. Zhao [b], Z. Li [a,*]

[a] School of Materials Science & Engineering, Central South University, Changsha 410083, China
[b] Department of Engineering, University of Liverpool, Liverpool L69 3GH, UK

ARTICLE INFO

Article history:
Received 3 September 2008
Received in revised form 9 February 2009
Accepted 26 March 2009

Keywords:
Magnesium alloy
Twin-roll casting
Microstructure
Texture

ABSTRACT

Twin-roll casting (TRC) technology has been applied to produce Mg–3Al–1Zn–0.2Mn alloy plates. The microstructure of the plates mainly consists of primary α-Mg and secondary $Mg_{17}(Al,Zn)_{12}$ phase. With directional solidification during the TRC process, deformation occurs preferentially near the surface and adjacent to the grain boundaries. Dislocation tangle, twins and recrystallized grains are visible in the TRC Mg–3Al–1Zn–0.2Mn plates. The plates show $\{0\,0\,0\,2\}$ texture in the sub-surface region and $\{1\,0\,\bar{1}\,4\}$ texture at the center.

1. Introduction

Twin-roll casting (TRC) is a promising technology for producing metals because of several advantages as compared with conventional ingot casting. It combines casting and hot rolling into a single operation: molten metal is fed into the gap between two internally water-cooled running rolls and, after having solidified and undergone some hot deformation, comes directly out as strips, sheets or plates [1–6]. This near-net-shape process can save energy, reduce cost and improve efficiency. TRC is especially attractive for Mg alloys, which have excellent specific strength and stiffness but low workability compared with other common structural alloys such as Al alloys and steels. TRC will potentially reduce the production costs, and thus increase the commercial applications of Mg alloys.

Up to date, TRC Al alloys have been widely studied and commercially produced [7–11]. The research work on TRC Mg alloys, however, is much less reported. The main investigations in the literature include: feasibility study of twin-roll casting process for magnesium alloys [1], the microstructure evolution and tensile properties of TRC Mg–Zn–Mn–Al alloys [2,3], the deformation behavior of TRC Mg–Zn–Mn–Cu–Zr alloy [4], and the effect of casting parameters on microstructure evolution of TRC AZ31B alloy [5]. In these studies, the textures of the TRC Mg alloys were not dealt with. Furthermore, the microstructure of a TRC Mg alloy is also dependent upon alloy composition and the manufacturing process. This paper investigates the microstructure and texture of a common TRC Mg alloy.

2. Experimental

AZ31B (nominal composition Mg–3Al–1Zn–0.2Mn in wt.%), one of the most extensively used wrought Mg alloy, was chosen in this study. TRC plates were prepared with a tilting twin-roll caster in CHINALCO Luoyang Copper Co. Ltd. The rolls have a diameter of 950 mm and length of 1800 mm. The gap between the two rolls was set at 5–6 mm. The rolls were preheated to 423–473 K before casting and carbon powder was used as lubricant. The raw metals were blended according to the composition, melted in a crucible and then delivered to the caster. The melt was protected by a shield gas (high purity N_2 with a small amount of SF_6) to prevent the molten alloys from burning and was at a temperature of 953–983 K before casting. Casting rate was regulated between 600 and 1200 mm min^{-1}. The plates obtained had a thickness of 6.5 mm.

Optical microscopy (OM) was used to examine the microstructure of the rolling plane, longitudinal section and transverse section of the TRC AZ31B plates. The surface to be examined was mechanically milled, polished, and then etched with a solution of ethanol (30 ml), picric acid (2 g), acetic acid (6 ml) and water (5 ml) to reveal the microstructure. A D/max 2500 X-ray diffractometer (18 kW) with Cu Kα radiation was used to obtain the diffraction patterns of the rolling plane, longitudinal section and transverse section. The plate was first sliced into two sheets such that the textures in the sub-surface and center regions of the plate were analyzed separately. Harris' method revised by Morris was employed to process the date [12] and subsequently inverse pole figures were drawn. A TecnaiG^{2}20 transmission electron microscope (TEM), operated at 200 KV and equipped with energy dispersive spectroscopy (EDS), was used to obtain details of microstructure. The thin foils for TEM observation were taken parallel to the transverse section, mechanically ground and then ion-beam milled to perforation.

3. Results and discussion

Fig. 1 shows representative optical micrographs of the rolling plane, longitudinal section and transverse section. On the rolling

* Corresponding author: Tel.: +86 731 8830264; fax: +86 731 8876692.
E-mail address: lizhou6931@163.com (Z. Li).

0254-0584/$ – see front matter
doi:10.1016/j.matchemphys.2009.03.026

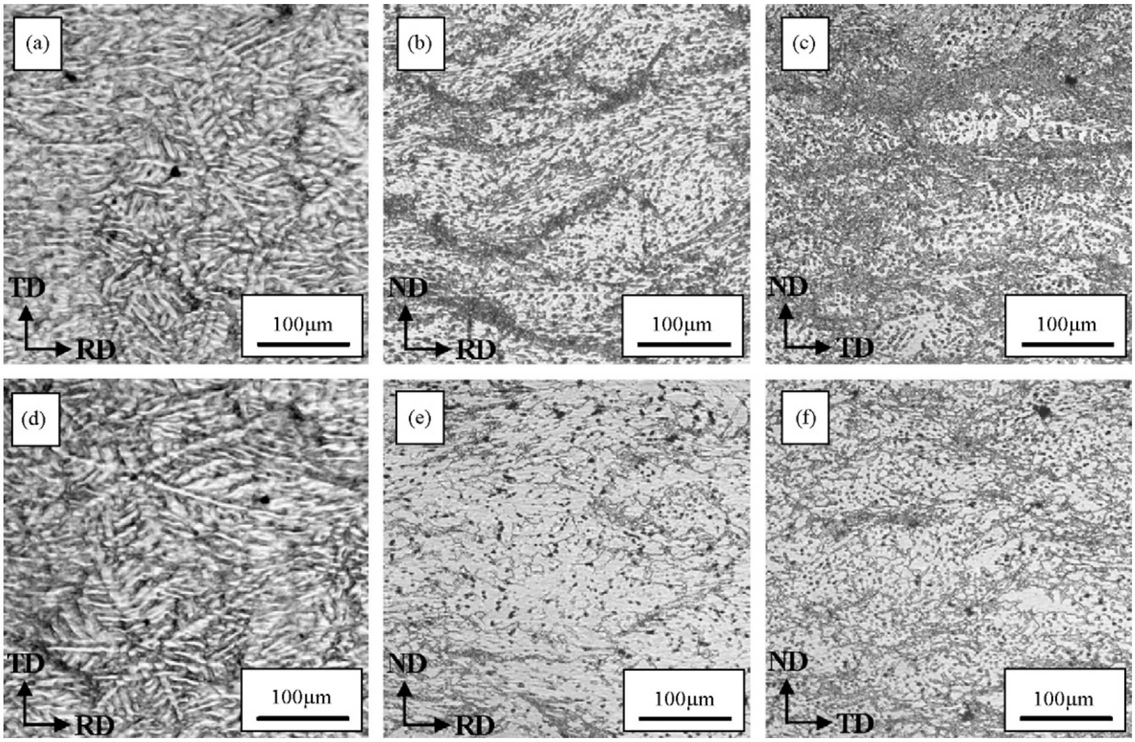

Fig. 1. Optical micrographs of the TRC AZ31B alloy. RD, TD and ND indicate the rolling, transverse and normal directions respectively. (a) Rolling plane of sub-surface region; (b) longitudinal section of sub-surface region; (c) transverse section of sub-surface region; (d) rolling plane of center; (e) longitudinal section of center; (f) transverse section of center.

plane, the dendritic structure is clearly displayed. The micrographs (Fig. 1a and d) show that the microstructure of the TRC AZ31B alloy mainly consist of primary α-Mg with the second phase (2–5 μm) dispersed in the interdendritic regions and along the grain boundaries [5,13]. On longitudinal and transverse sections (Fig. 1b, c, e, f), however, dendritic structure is nearly invisible and the deformation structure appears obviously, which can be attributed to the effect of rolling, the plate blank is compressed along the normal direction of the rolling plane by the rollers and then the dendritic structures on the longitudinal and transverse sections are destroyed by the plastic deformation during TRC process. Different microstructural features on the three planes indicate that the TRC plate is anisotropic, and the anisotropy is due to the complex TRC process, which will be analyzed in company with the texture results.

Moreover, the microstructures in sub-surface region and at the center are different either. On the longitudinal section, flow lines, prolonged grains and second phase particles are shown markedly in the sub-surface region (Fig. 1b), but not at the center (Fig. 1e). It is suggested that the deformation is macroscopically inhomogeneous, occurring severely in the region adjacent to the surface and slightly at the center. This phenomenon, also existent in TRC Al alloys [9,14], is due to the friction between the sheet and the rolls. The deformation in the sub-surface region is also microscopically inhomogeneous. As shown in Fig. 1c, the deformation occurs preferentially at grain boundaries because of stress concentrations at these regions. Large local strain and high temperature during the TRC process induce dynamic recrystallization [15,16], which is confirmed by the TEM analysis as described below.

The OM observations show that a large number of the second phase particles are more visible on the transverse section (Fig. 1c) because they are elongated along the rolling direction (Fig. 1b). For the convenience of observing these particles, TEM specimens

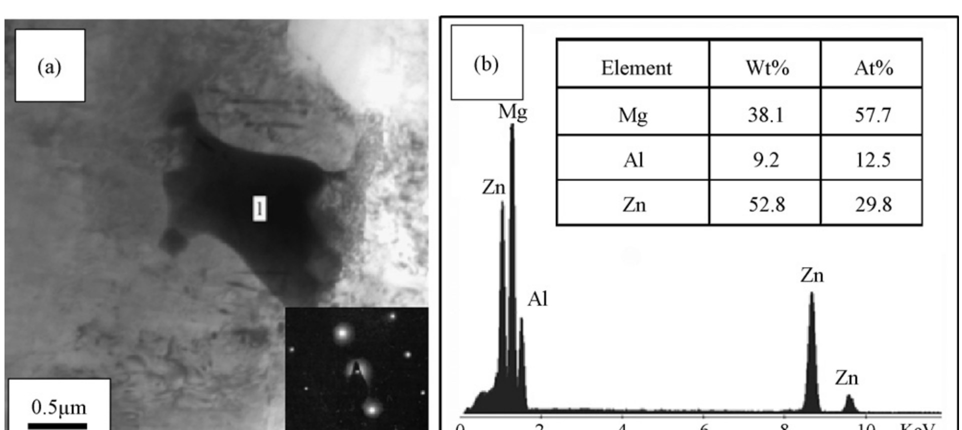

Fig. 2. TEM micrograph (a) and EDS spectrum (b) of the second phase in the TRC AZ31B alloy.

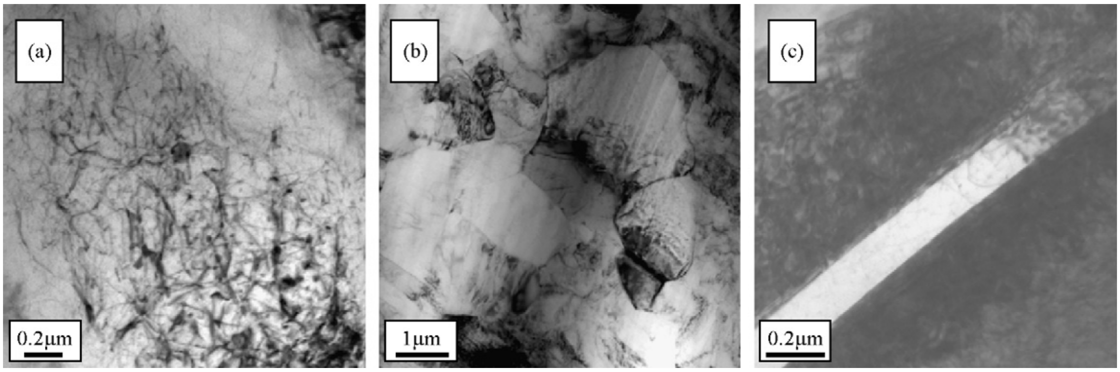

Fig. 3. TEM micrographs of the TRC AZ31B alloy: (a) dislocation tangle; (b) recrystallized grains; and (c) twins.

were taken parallel to the transverse section. The TEM micrograph, selected area diffraction patterns (SADP) and EDS analysis results (spectrum and the embedded table) of the second phase are shown in Fig. 2. It can be seen that the atomic ratio between Mg and (Al + Zn) in the second phase is approximately 17:12.46 (in view of measure error). It is reported in the literature [17] that the Al atoms in the $Mg_{17}Al_{12}$ phase can be partly replaced by Zn atoms to form an extended phase of $Mg_{17}Al_{12}$, $Mg_{17}(Al,Zn)_{12}$, which has a similar crystal structure to $Mg_{17}Al_{12}$ (body-centered cubic structure with the lattice parameter of 1.054 nm). By combining the analyses of EDS and SADP, the second phase in the TRC AZ31B plates is confirmed to be $Mg_{17}(Al,Zn)_{12}$. The existence of the $Mg_{17}(Al,Zn)_{12}$ phase in this alloy is due to non-equilibrium solidification. The cooling rate was higher for the alloying elements to diffuse adequately

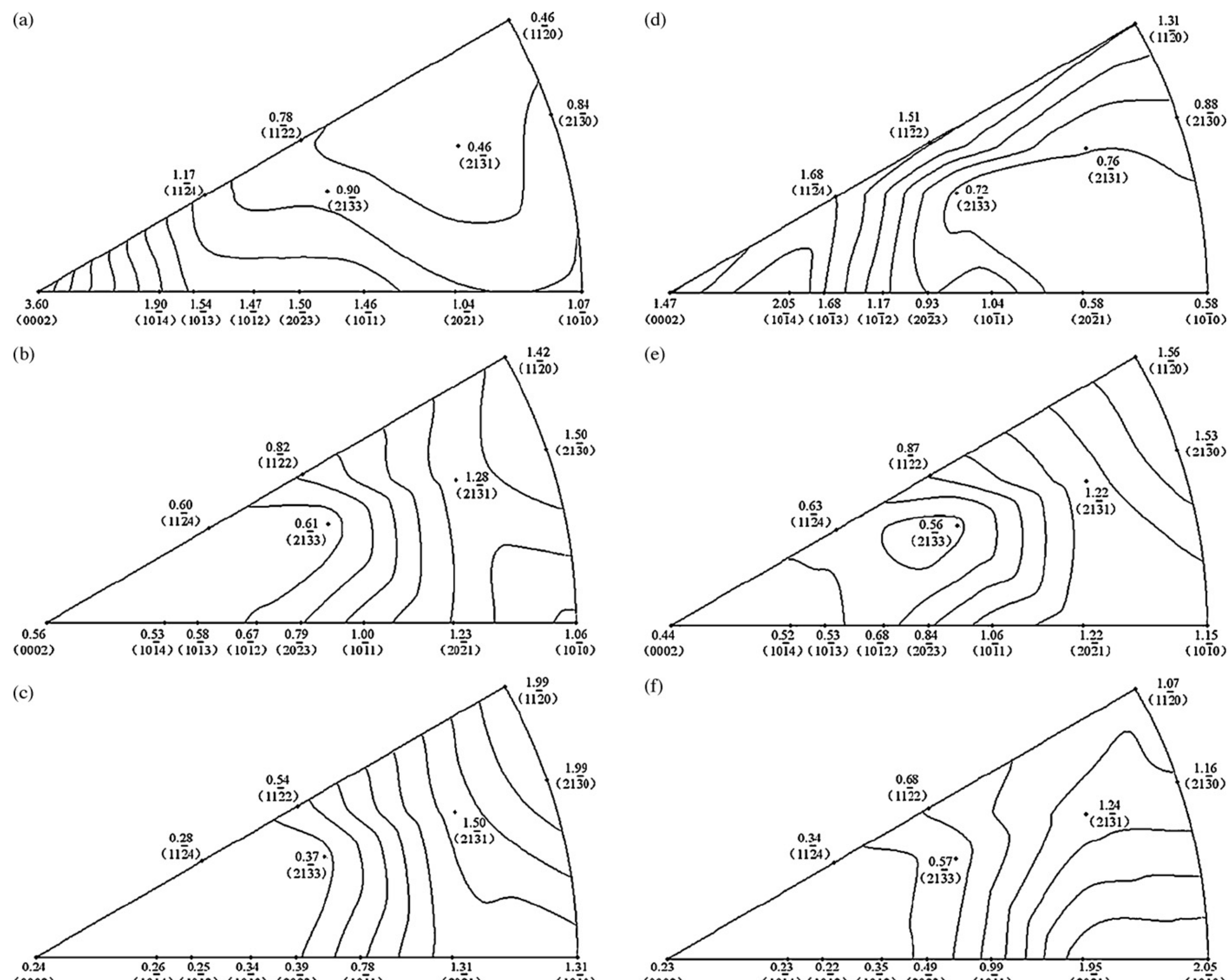

Fig. 4. Inverse pole figures of (a) rolling plane of sub-surface region; (b) longitudinal section of sub-surface region; (c) transverse section of sub-surface region; (d) rolling plane of center; (e) longitudinal section of center; and (f) transverse section of center.

in the solid during the TRC process. As a result, the solutes (Al and Zn) are enriched in the remnant liquid between the dendrite arms as the dendrites grow, and form $Mg_{17}(Al,Zn)_{12}$ in the end.

Fig. 3 shows the TEM micrographs of dislocation tangle, recrystalized grains and twins. It is reasonable to consider the deformation mechanism of hot working during TRC process to be similar to that of common hot working, which has been widely studied [15,16,18–20]. Although the number of slip systems in hexagonal close-packed (HCP) materials is limited at low temperatures, slip is the primary mechanism of plastic deformation in Mg alloys. At room temperature, plastic deformation in polycrystalline alloys has been considered to occur almost entirely by basal slip. At elevated temperature, the non-basal slip systems on prismatic and pyramidal planes could be activated [15,16]. The multiple slips lead to the dislocation tangle (Fig. 3a), and cross-slip and climb of dislocations form dislocation walls and polygonal cells [18]. As the deformation proceeds, large quantities of dislocations are reproduced and absorbed by the dislocation walls. The misorientations between the cells gradually increase, and the cells finally develop into recrystallized grains (Fig. 3b). It is well known that twinning is also an important mechanism of plastic deformation for Mg alloys at low temperature. Twins are also visible after hot working, although their quantity decreases as the deformation temperature increases [18]. In the TRC plates investigated in this study, a few twins, which are too thin to be observed by OM, are found in TEM (Fig. 3c).

As the OM analyses indicate that the TRC AZ31B plates are anisotropic and locally deformed, there is a necessity to investigate the texture of the plate. Fig. 4 shows the inverse pole figures of the rolling plane, longitudinal section and transverse section for the sub-surface region and the center. Comparing the inverse pole figures of the three planes shows that the result of the rolling plane is markedly different from that of the other two sections, with the basal plane of grains being more frequently parallel to the rolling plane. There is also an obvious difference in texture between the sub-surface region and the center. The sub-surface region exhibits a simple $(0\,0\,0\,2)\ [1\,1\,\bar{2}\,0]$ basal texture; the situation at center is more complex, with $\{1\,0\,\bar{1}\,4\}$ plane (at an angle of 25.1° with the basal plane) parallel to the rolling plane and $\langle 1\,0\,\bar{1}\,0\rangle$ direction parallel to the rolling direction. It is well known that the HCP structure only shows six-fold symmetry on basal plane, the results of texture analysis are well consistent with the OM observations (a plenty of the approximate six-fold symmetrical dendrites are showed on the rolling plane (Fig. 1a and d)).

The OM and texture analyses have clearly shown that orientation texture is formed in the TRC AZ31B plates. Directional solidification (DS) and subsequent hot rolling are considered to be the two dominant factors in the formation of texture [9]. During TRC, heat transfers from the molten metal to the rolls directionally, leading to directional solidification (DS). The solidified metal is then deformed by the running rolls. The final texture of the TRC plate is the combination of solidification texture and hot deformation texture. Texture formed after hot rolling is normally $\{0\,0\,0\,2\}$ basal texture, the formation of which is considered to be the result of the slip systems operating on basal planes [21–24]. The formation of DS texture, however, is more complex. As solidification process can be regarded as atoms moving from the liquid onto the surface of the solid crystal, DS texture is affected by crystal structure, temperature gradient, alloy component, solidification interface, and so on [25]. The solidification texture can also be influenced the flow of the molten metal [26], which is unavoidable in TRC. The formation of TRC texture and the microstructure anisotropy in the TRC AZ31B alloy are therefore an integrated effect of the multiplex factors mentioned above, and more work is required for a full analysis of the texture formation.

Homogenization treatment has to be performed after casting to dissolve the solvable phase and to reduce the amount of residual constituents in the matrix, so that the plasticity and the fatigue fracture resistance of the alloy can be increased. The process of homogenization treatment is based on the diffusion of the elements, therefore it should be carried out at certain temperature for a long time [5,6] and leads a prodigious consumption of energy and oxidation of materials. The plate investigated in this experiment has been undergone plastic deformation, and the crystal defects, such as vacancies and dislocations (Fig. 3a), were produced by the plastic deformation. These large quantities of crystal defects can accelerate the diffusion of elements and shorten homogenization heat treatment time. More over, the stored energy of plastic deformation will lead the static recrystallization during homogenization treatment [27], the softening of recrystallization facilitates the subsequent plastic deformation. The microstructure anisotropy which may decrease the plasticity and the fatigue fracture resistance can be mostly eliminated by homogenization treatment. Therefore, the magnesium alloy plate that fabricated by TRC in this paper is favorable for the subsequent heat treatment and plastic deformation. Whereas, more works are required to analysis the effects of TRC texture and microstructure anisotropy on properties of the alloy.

4. Conclusion

TRC technology has been applied to fabricate AZ31B plates, and the microstructure and texture of the as-produced plates have been investigated. The microstructure mainly consists of primary α-Mg with the second $Mg_{17}(Al,Zn)_{12}$ phase dispersing in interdendritic regions and along grain boundaries. During TRC, the plate undergoes hot deformation, which occurs preferentially near the surface and adjacent to the grain boundaries. Dislocation tangle and twins are visible in the TRC AZ31B plates. Dynamic recrystallization is induced in the regions with large strains. The TRC AZ31B plates show $\{0\,0\,0\,2\}$ basal texture in the sub-surface region, and $\{1\,0\,\bar{1}\,4\}$ texture at the center, due to DS and inhomogeneous deformation in TRC.

Acknowledgements

This study was supported by National Key Technology R&D Program during the 11th Five-Year Plan Period (2006BAE04B02). The authors would like to thank Dr. J.G. Tang for assistance in constructing the inverse pole figures.

References

[1] H. Watari, T. Haga, N. Koga, K. Davey, J. Mater. Process. Technol. 192–193 (2007) 300.
[2] S.S. Park, G.T. Bae, D.H. Kang, In-Ho Jung, K.S. Shin, Nack J. Kim, Scripta Mater. 57 (2007) 793.
[3] S.S. Park, Y.S. Oh, D.H. Kang, Nack J. Kim, Mater. Sci. Eng. A. 449–451 (2007) 352.
[4] S.X. Song, J.A. Horton, N.J. Kim, T.G. Nieh, Scripta Mater. 56 (2007) 393.
[5] D.Y. Ju, X.D. Hu, Trans. Nonferrous Met. Soc. China 16 (2006) s874.
[6] T. Mino, M. Asakawa, D. Lee, T. Fujiwara, K. Matsuzaki, M. Kobayashi, J. Mater. Process. Technol. 177 (2006) 534.
[7] M. Yun, S. Lokyer, J.D. Hunt, Mater. Sci. Eng. A 280 (2000) 116.
[8] T. Haga, S. Suzuki, J. Mater. Process. Technol. 143–144 (2003) 895.
[9] Ch. Gras, M. Meredith, J.D. Hunt, J. Mater. Process. Technol. 169 (2005) 156.
[10] Ch. Gras, M. Meredith, J.D. Hunt, J. Mater. Process. Technol. 167 (2005) 62.
[11] M. Slamova, M. Karlık, F. Robaut, P. Slama, M. Veron, Mater. Charact. 49 (2003) 231.
[12] S.T. Li, Basis of Crystal X-ray Diffraction, Metallurgical Industry Press, Beijing, 1990, p. 200 (in Chinese).
[13] A.K. Dahle, Y.C. Lee, M.D. Nave, P.L. Schaffer, D.H. StJohn, J. Light Metals 1 (2001) 61.
[14] B. Forbord, B. Andersson, F. Ingvaldsen, O. Austevik, J.A. Horst, I. Skauvik, Mater. Sci. Eng. A 415 (2006) 12.
[15] S.E. Ion, F.J. Humphreys, S.H. White, Acta Metall. 30 (1982) 1909.
[16] A. Galiyev, R. Kaibyshev, G. Gottstein, Acta Mater. 49 (2001) 1199.
[17] T.N. Jin, Z.R. Nie, D.X. Li, Chin. J. Nonferrous Metals 12 (2002) 110 (in Chinese).
[18] M.M. Myshlyaev, H.J. McQueen, A. Mwembela, E. Konopleva, Mater. Sci. Eng. A 337 (2002) 121.
[19] L. Helis, K. Okayasu, H. Fukutomi, Mater. Sci. Eng. A 430 (2006) 98.
[20] J.C. Tan, M.J. Tan, Mater. Sci. Eng. A339 (2003) 124.

[21] G.S. Rao, Y.V.R.K. Prasad, Metall. Trans. A 13 (1982) 2219.
[22] Y.N. Wang, J.C. Huang, Mater. Chem. Phys. 81 (2003) 11.
[23] M.T. Perez-Prado, J.A. del Valle, O.A. Ruano, Scripta Mater. 50 (2004) 667.
[24] T. Mukai, M. Yamanoi, H. Watanabe, K. Higashi, Scripta Mater. 45 (2001) 89.
[25] A. Hellawell, P.M. Herbert, Proc. R. Soc. Lond. A 269 (1962) 560.
[26] M.I. Bergman, S. Agrawal, M. Carter, M. Macleod-Silberstein, J. Cryst. Growth 255 (2003) 204.
[27] Yucel Birol, J. Mater. Process. Technol. 209 (2009) 506.