Journal of Alloys and Compounds 502 (2010) 382–386

Contents lists available at ScienceDirect

Journal of Alloys and Compounds

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

An investigation on DC casting of a wrought aluminium alloy at below liquidus temperature by using melt conditioner

R. Haghayeghi[a,*], E.J. Zoqui[b], N.R. Green[c], H. Bahai[a]

[a] H106, Howell Building, Design & Eng Dept, Brunel University, Uxbridge, Middlesex UB8 3PH, UK
[b] Faculty of Mechanical Eng, The State University of Campinas, Postal Code: 6122, CEP 13081-970, Campinas, Sao Paulo, Brazil
[c] Metallurgy and Materials, The University of Birmingham, Edgbaston, Birmingham B15 2TT, UK

ARTICLE INFO

Article history:
Received 8 March 2010
Accepted 24 April 2010
Available online 4 May 2010

Keywords:
Wrought alloy
DC casting
Microstructure

ABSTRACT

The application of Melt Conditioner (MC) for production of high-quality DC billets and slabs at semisolid state is examined. In this technique, liquid metal is continuously fed into a twin-screw melt conditioning device, where the liquid metal or semisolid slurry is subjected to high shear rate, and then delivered continuously into a DC caster. In this paper, the feasibility of MCDC of a wrought aluminium alloy in the semi solid state has been investigated and the possibility of DC casting by MC technique below the liquidus temperature as a novel idea was explored. This idea may challenge the conventional DC casting which is normally performed above liquidus temperature.

1. Introduction

One of the main characteristics of a proper ingot or alloy is fine and uniform microstructure. However, most of the ingots which are produced by DC casting not only do not have uniform microstructure but also potentially contain defects such as hot tearing, cracks and anisotropic grain sizes [1]. Some methods have been suggested to resolve the above problems such as Magneto Hydro Dynamic (MHD) stirring [2] or Electro Magnetic Stirring (EMS) [3]. However, these techniques have their own problems such as complexity, size of ingot and production rate. To address these problems, Brunel Centre for Advanced Solidification Technology (BCAST) recently developed a novel processing technique, Melt Conditioner Direct Chill (MCDC) casting [4,5]. MCDC is more efficient in energy and cost, produces high quality ingots with fine and uniform microstructure and does not have the restrictions of other methods. By applying intensive shearing, not only the problems of columnar microstructure and macrosegregation are resolved, but also fine and uniform structure is achieved across the ingot [5]. This technique consists of a twin screw Melt Conditioner (MC) device [6,7] and a DC caster, in which liquid metal is delivered continuously into the twin screw melt conditioner and after intensive shearing the conditioned liquid metal, is poured into the DC caster. The result of this process is a fine microstructure achieved by exploiting solidification under high shear stress and rate. This process not only offers a high quality feedstock, but also enhances nucleation and grain refinement [8], resulting in a fine and uniform microstructure which improves ingot properties [9,10].

In this paper, the feasibility of applying the MCDC technique with 7075 aluminium alloy below the liquidus temperature has been investigated with the intension of producing semi-continuous cast billet. Moreover, performance of DC casting for wrought aluminium alloys at semisolid state as a novel idea was investigated. Furthermore, the microstructural evolution of the billet has been studied and the mechanisms of structure refinement by MCDC explored; resulting structures have been analysed and compared with conventional DC cast specimens.

2. Experimental procedure

The MCDC equipment consists of two basic functional units (Fig. 1). The MC device consists of a pair of co-rotating, fully intermeshing and self-wiping screws. The screws have a profile designed to achieve high shear rate and high internal turbulence. A coating of molybdenum disilicide is applied to the screws to hinder reaction with the molten aluminium alloys. The barrel is made of special grade cast iron. The operating temperature is monitored and controlled by 4 R-type thermocouples inserted through the barrel and located close to the screws.

For testing the feasibility of the process, 5 kg charges of 7075 aluminium alloy ingot supplied by Smith's Metal Centres Ltd., was melted in a resistance furnace in a graphite crucible, the furnace temperature was set at 750 °C to melt the ingot. The alloy composition is given in Table 1.

After melt preparation, the sample was poured into the twin screw and sheared for 60 s at 800 rpm at 630 °C (with a corresponding volume solid fraction of 20% [11]), after which the slurry was fed into the DC caster. A baseline DC sample was cast without shearing for comparison. Cylindrical ingots of diameter 70 mm and length 140 mm were cast with a water flow rate of 78 L/min, a cooling rate of 3.5 K/sec and casting speed of 85 mm/min.

---

* Corresponding author.
E-mail address: mepgrrh@brunel.ac.uk (R. Haghayeghi).

0925-8388/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.jallcom.2010.04.173

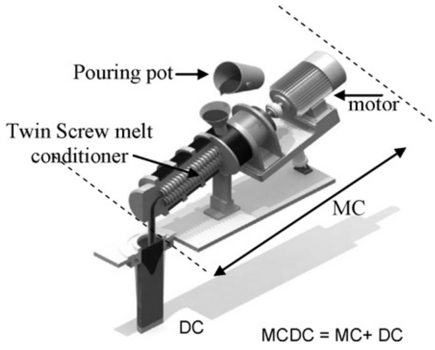

Fig. 1. Schematic illustration of MCDC process.

Table 1
Chemical composition of the 7075 Al alloy in wt%.

Zn	Mg	Cu	Cr	Fe	Mn	Ti	Si	Al
5.56	1.95	1.64	0.19	0.10	0.03	0.01	0.07	Bal.

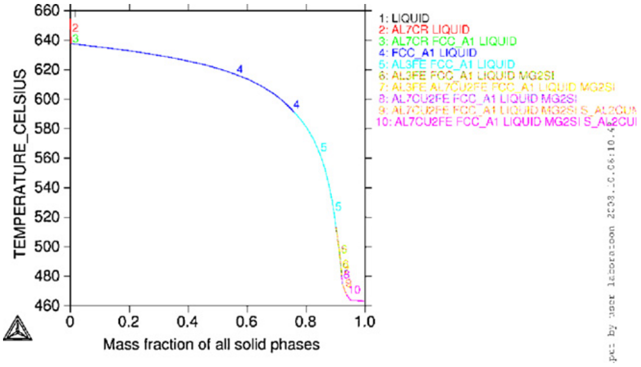

Fig. 2. Thermo-calc analysis of AA7075.

In order to investigate the microstructural features of the produced ingots, samples were cut, ground, polished and anodised at an optimum voltage of (20–40 V/cm^2) in a 2% aqueous solution of tetra fluoroboric acid (HBF_4), revealing the grain structure. Samples were examined under polarized light and the grain sizes measured according to standard ASTM E112-96, linear intercept method [12]. The error bars were calculated from (screen of 100 μm × 100 μm of) analysing several pictures and standard deviations were calculated. Chemical compositions were measured across the ingot in increment of 10 mm using a foundry master spectrograph (Worldwide Analytical System-AG). In order to understand the solidification sequence of AA7075, Thermo-Calc analysis was performed using Scheil equation.

3. Results

Results of Thermo-Calc analysis are shown in Fig. 2. It was observed that the first phase to form within the liquid during solidification is Al_7Cr. Further with progression of solidification, the following phases were formed: Al, Al_3Fe, Mg_2Si and Al_7Cu_2Fe.

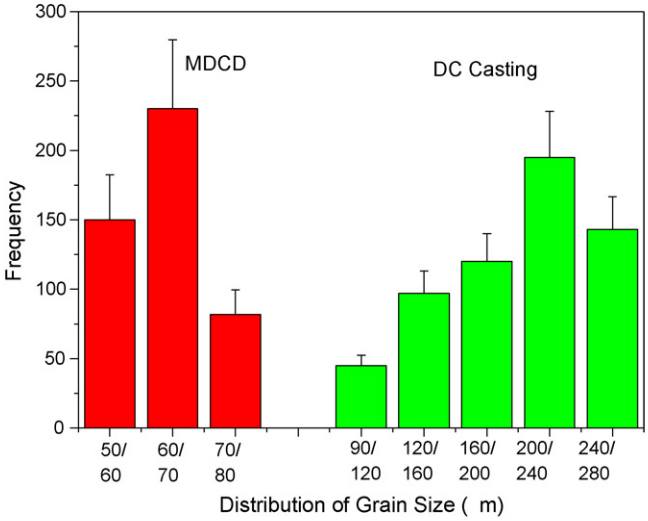

Fig. 4. The grain size distribution of MCDC process and DC processed ingot (transverse section).

The microstructures of transverse sections of both MCDC and DC specimens from edge to centre are shown in Fig. 3. The MCDC billet (a) shows a significantly refined microstructure compared to the DC billet (b). The microstructure of the MCDC, shows fully equiaxed grains and a uniform grain size across the billet. On the other hand, the DC ingot comprises a near equiaxed microstructure at the centre and pseudo columnar structure at the edge and a non-uniform equiaxed grain size across the billet.

The distribution of grain sizes in the MCDC process and DC casting is plotted in Fig. 4. In the MCDC samples, the grain size varies between 50 and 80 μm whereas in the DC cast specimen the grain size varied between 90 and 280 μm.

Fig. 4 indicates two points, (1) the grain size distribution in the MCDC process is narrower in comparison to DC casting, and (2) the effect of shearing is dominant in the MCDC in which most of the grains have been distributed between 60 and 70 μm.

Fig. 5a and b shows the variation of the grain size and the chemical composition for MCDC process from edge to the centre of the ingot. In Fig. 5a, the grain size of MCDC is in average 63 μm whilst in the DC casting, the average grain size is 207 μm. Also the chemical composition variation throughout the ingot was carried out which is constant in the entire MCDC ingot (Fig. 5b). However, in the DC ingot due to shell segregation and partial re-melting of the shell during the dwell time in the air gap region, the distribution of the alloy elements can not be uniform [13] (Fig. 5c).

Fig. 5 implies that applying the MCDC can provide fine and uniform microstructure across the ingot and reduce macro-segregation properly, whilst in the conventional casting non-uniform structure/chemical composition distribution are observed.

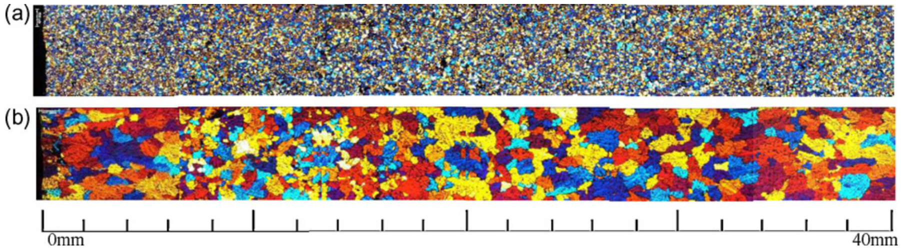

Fig. 3. Micrographs of MCDC and DC processes, (a) MCDC, (b) DC sample surface to the left.

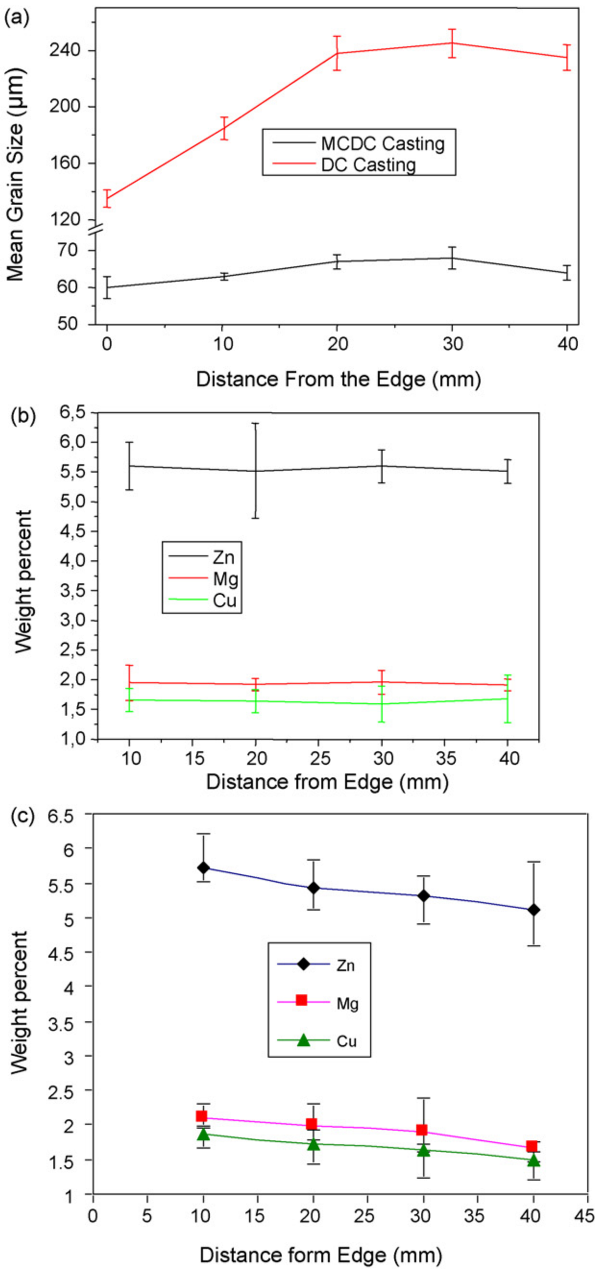

Fig. 5. (a) Spatial variation of grain size in MCDC and DC billets, (b) variation of chemical composition in MCDC billet, (c) chemical composition in DC billet.

4. Discussion

4.1. Grain refinement mechanism

There are few possibilities that can be suggested for refinement of the structure by MCDC method. Those have been described briefly below:

(1) *Rapid Cooling+ Agitation*: Rapid cooling can decrease the grain size of an alloy [14]. In other words, due to large ratio of surface area to volume in the melt conditioner, heat extraction is encouraged and rapid cooling is occurred (7 °C/s), thus solid nuclei can be formed on the surfaces. With further agitation or intensive shearing of the melt, the formed nuclei are distributed uniformly across the melt. Indeed, due to shearing, uniform temperature and composition are obtained which promote equiaxed growth.

(2) *Cavitation*: Shearing like as ultrasonic waves by the help of cavitation can contribute to heterogeneous nucleation [15–17]. The suggested mechanism include improved wetting, local undercooling upon collapse of cavitation bubbles and pre-solidification of particles inside fine capillaries. The cavitation occurs more easily at higher temperature where the density of liquid is less. However, this mechanism is ruled out as the melt cooled rapidly to the semisolid state in which the formed cavities can not be stable.

(3) *Aluminides Refinement*: The results of AA5754 by Haghayeghi et al. [18] showed shearing could significantly improve refinement when the intermetallics are available (such as Al_3Fe). Indeed, Eskin [19] suggests aluminides in aluminium alloys also grain refine alloys, even above the liquidus temperature. However, the only aluminide which is available above the liquidus temperature is Al_7Cr, but due to its different crystal structure, this aluminide can not act as substrate.

In fact, in the MC machine the experimental condition is similar to the Martinez and Flemings [20] study. In their experiment they agitated the melt and cooled it rapidly from close liquidus temperature. Similarly, in the MC machine the melt is cooled rapidly from temperature above liquidus whilst sheared. Large ratio of surface area to volume in addition to fragmentation of grains encourages heterogeneous nucleation and further uniform distribution of nuclei. Consequently, it is suggested, shearing followed by rapid cooling can be acknowledged as the main factors for refinement of the structure.

4.2. Solidification process in melt conditioner

By applying the MCDC technique, two stages of solidification take place. Primary solidification occurs in the melt conditioner in which the liquid is sheared which results in distributing nuclei and growing them partially at semisolid range. The dominant action at this stage is the distribution of nuclei in the semisolid temperature range. The second stage of solidification occurs inside the DC caster with an appropriate cooling rate in the absence of shearing. At this stage, the nuclei that have been formed and distributed uniformly in the first stage would activate due to the applied cooling rate. In consequence, all the nuclei would be able to survive and grow. This, results in a fine and uniform microstructure. So, an ingot with fine and uniform microstructure is achieved. The novelty of this technique in this paper is producing a DC ingot at below liquidus temperature. The dynamic solidification process of MC machine is shown in Fig. 6.

4.3. Solidification in DC casting

In contrast in conventional casting the un-sheared melt is poured directly into the mould and solidification starts from the mould wall. Due to different cooling rate at different positions of the ingot as well as shell formation around the sump and the air gap, the structure would not be uniform (Fig. 4). Moreover, just some of the nuclei would survive due to convection and re-melting, which result in non-consistent structure. The produced ingots by this method have an improper microstructure with many defects such as cracks. In fact, because of uneven cooling in different regions of the ingot, thermal stresses are generated, which may induce cracks. These might propagate, leading to an ingot failure if the thermal stresses increase. Further; shell segregation may occur which is difficult to avoid regarding DC casting conditions (Fig. 5c).

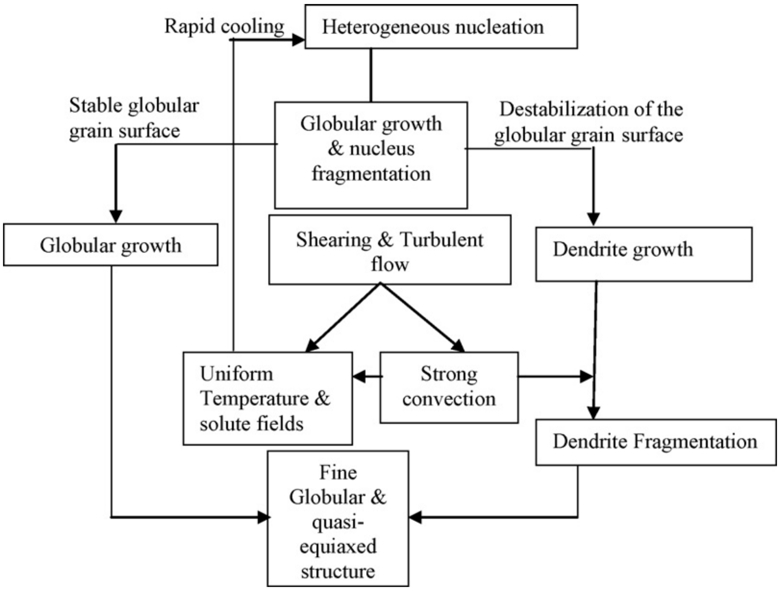

Fig. 6. The outline of dynamic.

4.4. *Microstructural evolution in MC technique*

By applying the MCDC technique, the problems of conventional casting can be eliminated. As for non-uniform microstructure in conventional casting, MCDC helps nuclei to survive and form them that can contribute to the solidification and growth. In fact, the entire ingot from edge to the centre has active nuclei contributing in the process, which offers a fine and uniform microstructure. Moreover, the slurry is not poured at relatively high temperature like DC casting and is consistent in temperature and composition. So, thermal stresses due to fairly low temperature in comparison to DC casting are not considerable. Also no macro-segregation is seen due to the controlled volume fraction and the characteristics of flow between solid and liquid phase. Further, due to lower viscosity in MCDC process, melt flows more smoothly and the associated problems of melt flow in DC casting (segregation and columnar grains) would be restricted [21].

Martinez and Flemings [20] study is close to MC machine experimental conditions. They kept the slurry isothermally and sheared the melt at 60 s with 409 rpm; the achieved grain size was 60 μm. In the MC at 60 s with 800 rpm, grain size of 63 μm was acquired. Further, by using cooling slope by Tanabe et al. [22], Motegi and Tanabe [23] and Guan et al. [24], all got the grain size of around 56–60 μm. It seems in all cases the grain size in the semisolid range can not be below 55 μm. This would imply fragmentation of grains can be extended up to a certain limit and thereafter ripening would occur.

By comparing the microstructure of sheared samples above and below liquidus temperature, it seems by shearing above liquidus the grain size would be around 120 μm [25], whilst in the semisolid sheared samples grain size of 63 μm was achieved. Haghayeghi et al. [25] showed when a melt is sheared above liquidus the grain size becomes eight times smaller than conventional casting. With addition of grain refiner of 0.4 wt% of Al-5Ti-1B master alloy to the melt without shearing the grain size becomes 8000 times smaller. More over, by applying shear in combination with grain refiner (0.4 wt% of Al-5Ti-1B master alloy) the acquired grain size would be 64,000 times finer than conventional casing. However, by applying MC machine below liquidus grain size of 63 μm is achieved (43,000 times smaller). It means shearing below liquidus temperature would be more effective than shearing above. This can be verified by comparison of MC grain size with inclined cooling slope (CS), where the grain size of 56 μm can be achieved by applying CS whilst with Melt conditioner no grain size of less than 63 μm is acquired [22,25]. In fact, in CS due to continuous fragmentation numerous crystals are generated and the grain size would be 125,000 times smaller than conventional casting.

Results of 7075 processed by MCDC method at below liquidus temperature imply fine and uniform structure across the produced ingot and restricted macro-segregation throughout the sample. As presented, the grain size achieved in the MCDC is constant and around 63 μm and the grain distribution is narrower. In the conventional process, a grain size of 207 μm is achieved in average and a wider distribution of grains is achieved leading to disappropriate properties.

5. Conclusion

In summary, the MCDC as a well-developed technology is reported. This technology is a combination of DC casting and a (Melt Conditioner) MC machine. MCDC technique demonstrates an alternative method for producing billets and slabs at below liquidus temperature. The produced billets by this technology have a uniform and fine microstructure with consistent chemical composition throughout the cross-section of the billet. Heterogeneous nucleation due to large surface area to volume (Rapid cooling) in combination with intensive shearing would encourage the grain refinement of A7075 structure. It is thought, the above-mentioned combination is responsible for nucleation. Comparing the results of shearing below and above liquidus temperature imply shearing at semisolid range may result in 125,000 times smaller grain size than conventional casting whilst shearing above liquidus decrease the grain size by the order of eight. This achievement may challenge the idea of shearing above liquidus.

Acknowledgements

The Authors would like to thank Professor Z. Fan for his great contribution to this research. Also our great appreciation to Prof. G.M. Scamans, Prof. D.G. Eskin, Dr. E. McAlpine, Dr. N. Hari-Babu and R. Keyte for their useful debates. The authors would like to deliver their special thanks to Professor Nick Green for his fruitful comments and discussions on the paper. Indeed, the authors express their gratitude to Innoval Technology Ltd and other contributor companies for their technical supports and DTI (Department of Trade and Industry of the UK) for their financial support.

References

[1] D.G. Eskin, Suyitno, L. Katgerman, Prog. Mater. Sci. 49 (2004) 629–711.
[2] C. Vives, Proceedings of 2nd International Conference on Semisolid Alloys and Composites, MIT/Boston, USA, 1992, pp. 436–439.
[3] J.P. Gabathuler, D. Barras, 2nd International Conference on Semisolid Processing of Alloys and Composites, MIT/Boston, USA, 1992, pp. 33–46.
[4] Z. Fan, S. Ji, M.J. Bevis, PCT Patent, WO 02/13993A1 (Priority date: 11/08/2000).
[5] http://www.brunel.ac.uk/550/BCASTTechnologies/DCRCTech.doc.
[6] Z. Fan, M. Bevis, S. Ji, Patent PCT/WO 01/21343 A1 (1999).
[7] Z. Fan, G. Liu, Acta Mater. 53 (2005) 4345–4357.
[8] Z. Fan, G. Liu, M. Hitchcock, Mater. Sci. Eng. A 413–414 (2005) 229–235.
[9] S. Ji, Z. Fan, M.J. Bevis, Mater. Sci. Eng. A 299 (2001) 210–217.
[10] Z. Fan, X. Fang, S. Ji, Mater. Sci. Eng. A 412 (2005) 298–306.
[11] S. Chayong, H.V. Atkinson, P. Kapranos, Mater. Sci. Eng. A 390 (2005) 3–12.
[12] Standard Test for Determining Average Grain Size, vol. 14, ASTM International, PA, USA, 2002, pp. 256–281.
[13] R.D. Nadella, G. Eskin, Q. Du, L. Katgerman, Prog. Mater. Sci. 53 (2008) 421–480.
[14] M.C. Flemings, Metall. Trans. B 22B (1991) 269–293.
[15] C.E. Brennen, Cavitation & Bubble Dynamics, Oxford University Press, Oxford, 1995.
[16] R. Haghayeghi, E.J. Zoqui, D.G. Eskin, H. Bahai, J. Alloys Compd. 485 (2009) 807–811.
[17] Z. Fan, Y. Wang, M. Xia, S. Arumuganathar, Acta Mater. 57 (2009) 4891– 4901.
[18] R. Haghayeghi, E.J. Zoqui, H. Bahai, J. Alloys Compd. 481 (2009) 358–364.
[19] D.G. Eskin, Z. Metallkd 87 (1996) 295–299.
[20] R.A. Martinez, M.C. Flemings, Metall. Mater. Trans. A 36A (2005) 2205–2210.
[21] A.N. Turchin, D.G. Eskin, L. Katgerman, Mater. Sci. Eng. A 413–414 (2005) 98–104.
[22] F. Tanabe, T. Motegi, E. Sugiyama, Jpn Inst. Technol. 7 (2003) 290–294.
[23] T. Motegi, F. Tanabe, 8th International Conference on Semi Solid Processing of Alloys and Composites, Cyprus, 2004, p. 7.
[24] R.G. Guan, F.R. Cao, L.Q. Chen, J.P. Li, C. Wang, Mater. Proc. Technol. 209 (2009) 2592–2601.
[25] R. Haghayeghi, Y. Liu, Z. Fan, Solid State Phenom. 141–143 (2008) 403–408.