Materials Letters 161 (2015) 595–600

Contents lists available at ScienceDirect

Materials Letters

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

Effect of a transverse magnetic field on the growth of equiaxed grains during directional solidification

Xi Li [a,b,*], Jiang Wang [a], Dafan Du [a], Yikun Zhang [a], Yves Fautrelle [b], Henri Nguyen-Thi [c], Annie Gagnoud [b], Zhongming Ren [a], Rene Moreau [b]

[a] State Key Laboratory of Advanced Special Steels, Shanghai University, Shanghai 200072, PR China
[b] SIMAP-EPM-Madylam/G-INP/CNRS, PHELMA, BP 75, 38402 St Martin d'Heres Cedex, France
[c] Aix Marseille University, Campus Saint-Jerome, Case 142, 13397 Marseille Cedex 20, France

ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form
3 September 2015
Accepted 6 September 2015
Available online 10 September 2015

Keywords:
Equiaxed grains
Magnetic field
TE magnetic effects
Directional solidification

ABSTRACT

The effect of a transverse magnetic field on the growth of equiaxed grains during directional solidification of Al-10wt% Cu alloys was investigated experimentally and numerically. The experimental results show that the magnetic field has a great influence on the size and distribution of equiaxed grains. Indeed, the magnetic field causes refined and coarsen equiaxed grains to distribute on the both sides of the sample, respectively. *In-situ* synchrotron X-ray imaging shows that a transverse magnetic field induced some force which can act on equiaxed grains and cause the movement of equiaxed grains during directional solidification. Numerical results reveal that the modification of the structure may be attributed to the thermoelectric (TE) magnetic effects produced by the magnetic field. Furthermore, a new method of removing inclusions in molten metal is developed by means of the TE magnetic force.

1. Introduction

The magnetic field has been used in metallurgical processes for several decades and brings an unprecedented approach to realize the non-contact control of flows in the melt. Traditionally, the static magnetic field can suppress or damp the liquid motion due to the braking effect of the Lorentz force [1–3]. However, Boettinger et al. found that a transverse and axial magnetic field of 0.1 T has no influence on the microstructure or longitudinal macrosegregation during the directional solidification of the near-eutectic Pb-57 wt% Sn alloy [4]. Tewari et al. [5] observed that the cellular array was severely distorted when a Pb-17.7 wt% Sn alloy was solidified vertically at very low pulling rates (less than 1 μm/s) under a 0.45 T transverse magnetic field.. Alboussière [6] and Laskar [7] found that a 0.6 T transverse or a 1.5 T axial magnetic field caused the appearance of large freckles in the solidified vertically Bi-60 wt% Sn and Cu- 45 wt% Ag, which indicated new flow has been created in the liquid bulk. Furthermore, Alboussière et al. [6] suggested that this new flow was induced by the interaction between the magnetic field and TE effects, and subsequently, Lehmann [8] offered some experimental evidence for the thermo electromagnetic convection (TEMC). In our previous works, some experiments have been performed to uncover the effects of the TE magnetic force in various phenomena, such as dendritic and cellular growth [9], interface instability [10], and the columnar-to-equiaxed transition (CET) [11]. However, so far, little work has been done to investigate the effect of the TE magnetic effects on the growth of equiaxed grains.

The present work studied the effect of a transverse magnetic field on the growth of equiaxed grains during directional solidification. The experimental results show that the application of the magnetic field affected the size and distribution of equiaxed grains significantly. Indeed, refined and coarsen equiaxed grains appeared on two sides of the sample under the magnetic field, respectively. *In-situ* synchrotron X-ray imaging shows that some force has acted on equiaxed grains and induced the movement of equiaxed grains during directional solidification under a transverse magnetic field. Numerical results reveal that the TE magnetic effects may be responsible for the above results. Further, a new method to remove inclusion in molten metal is proposed by means of the TE magnetic force.

2. Experimental

The Al-10 wt% Cu alloy used in this work was prepared by high-purity Al (99.99%) and Cu (99.99%) in a graphite crucible induction furnace. The molten alloy was heated to 950 °C and magnetically stirred for half an hour, then poured into a graphite mold to cast

* Corresponding author at: State Key Laboratory of Advanced Special Steels, Shanghai University, Shanghai 200072, PR China. Fax: 00330476825211.
E-mail address: lx_net@sina.com (X. Li).

http://dx.doi.org/10.1016/j.matlet.2015.09.026
0167-577X/

samples with inner diameter of 3 mm and length of 200 mm. The cast sample was enveloped in a high-purity corundum tube with 3 mm in the inner diameter and 200 mm in the length for the directional solidification experiment. The samples were directionally solidified in Bridgman–Stockbarger type furnace at a specified growth speed under various magnetic field intensities. The transverse static magnetic field was produced by a static electromagnet with an adjustable intensity up to 1.0 T. To control the furnace temperature, a NiSi–NiCr thermocouple with the precision of ± 1 K was placed in the furnace. A water-cooled cylinder containing liquid Ga–In–Sn metal (LMC) was used to cool down the specimen. The temperature gradient in the sample was controlled by adjusting the furnace temperature, which was isolated from the LMC by a refractory baffle. The device was designed such that the specimen moves downward while the furnace remains stationary. The growth speed was controlled by a servo motor and could be continuously adjusted between 0.5 μm/s and 3000 μm/s. Microstructures of the samples obtained from the

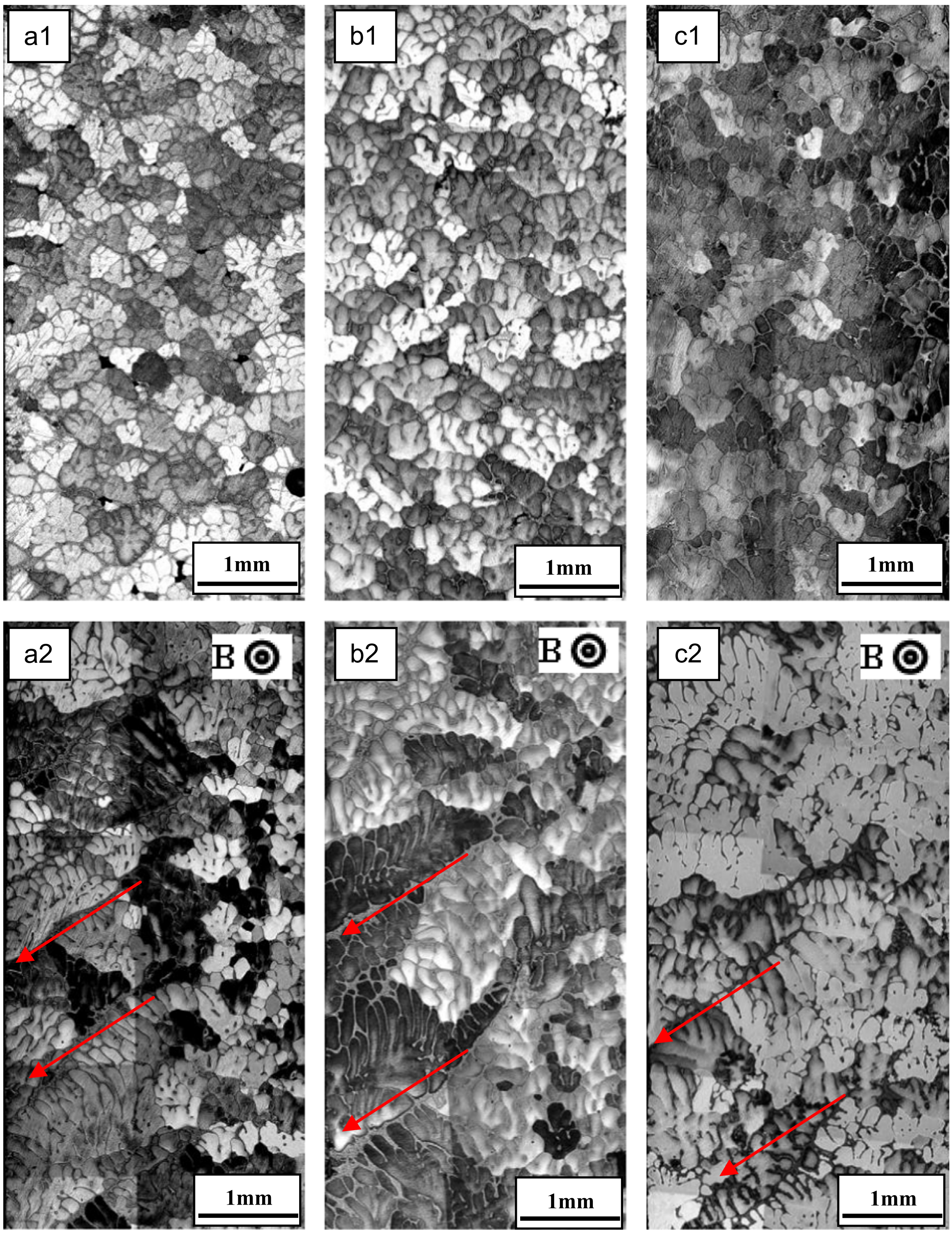

Fig. 1. Longitudinal structures in directionally solidified Al-10 wt% Cu alloy at various growth speeds with and without a 0.3T-transverse magnetic field: (a) 10 μm/s; (b) 20 μm/s; (c) 30 μm/s.

experiments were investigated in etched condition by the optical microscope and the EBSD in a high-resolution scanning electron microscope equipped with the Channel 5 EBSD system (HKL Technology Oxford Instrument).

3. Experimental results and discussion

Fig. 1 shows longitudinal structures in directionally solidified Al-10 wt% Cu alloys at various growth speeds with and without a 0.3 T transverse magnetic field. One can notice that in the case of no magnetic field, the equiaxed grains uniformly distribute on the whole sample. When the transverse magnetic field is applied, refined and coarsen equiaxed grains appear on the both sides of the sample, respectively. Further, the EBSD technology was used to analyze the morphology of the solidification structure. Fig. 2 shows the EBSD maps for the structures in directionally solidified Al-10 wt% Cu alloys at the growth speed of 20 μm/s under various transverse magnetic fields. Under the magnetic field, the refined grains appear on the right side of the samples and the refined region as well as the size of the refined grains decrease as the magnetic field increases (see Fig. 2(a) and Fig. 2(b)). Fig. 2(c) shows the size of the grains as a function of the magnetic field and the distance from the left of the sample. One can see that the deflected dendrites have been formed on the left of the sample under the magnetic field (see Fig. 2(b2)–(b4)).

To study the information mechanism of the structures under the magnetic field, the *in-situ* Synchrotron X-ray radiography has been performed. Fig. 3 shows the successive *in-situ* Synchrotron X-ray images during directional solidification with and without a 0.08 T transverse magnetic field. One can observe that in the case of no magnetic field, due to the gravity, the grain moves down. However, when the magnetic field is applied, equiaxed grains move approximately along the direction perpendicular to the magnetic field, as shown in Fig. 3(b). This result suggests that some force has acted on equiaxed grains during directional solidification under a transverse magnetic field. Moreover, the refined grains appear on the right of the sample under the magnetic field, which is good agreement with the results as shown in Fig. 1 and Fig. 2.

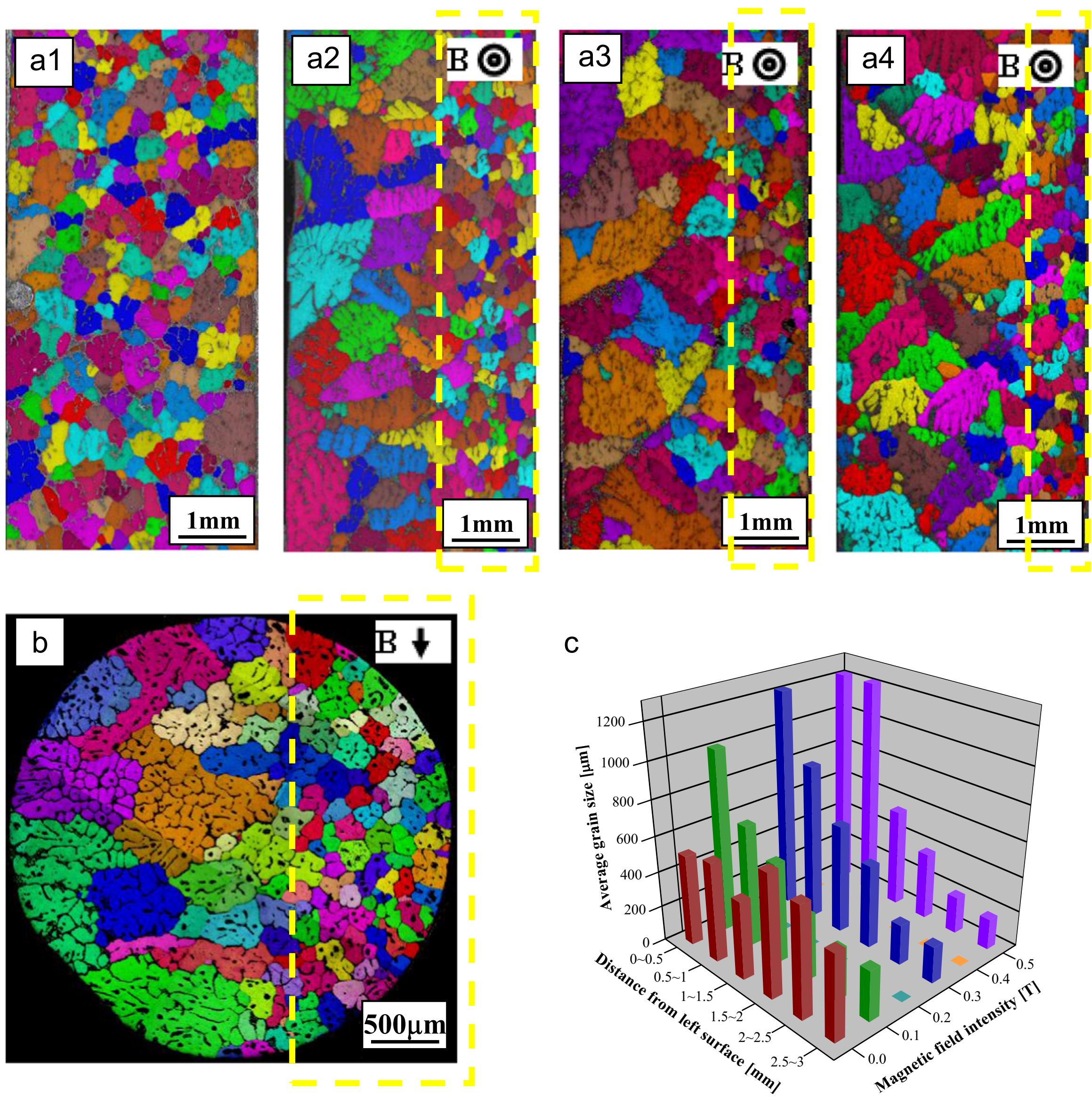

Fig. 2. EBSD maps for the structures in directionally solidified Al-10 wt% Cu alloy at the growth speed of 20 μm/s under various transverse magnetic fields: (a) Longitudinal structures, (a1) 0 T, (a2) 0.1 T, (a3) 0.3 T, (a4) 0.5 T; (b) transverse structure, 0.1 T; (c) the size of the α-Al grains as a function of the magnetic field and the distance from the left side of the sample. Yellow panes marking refined region.

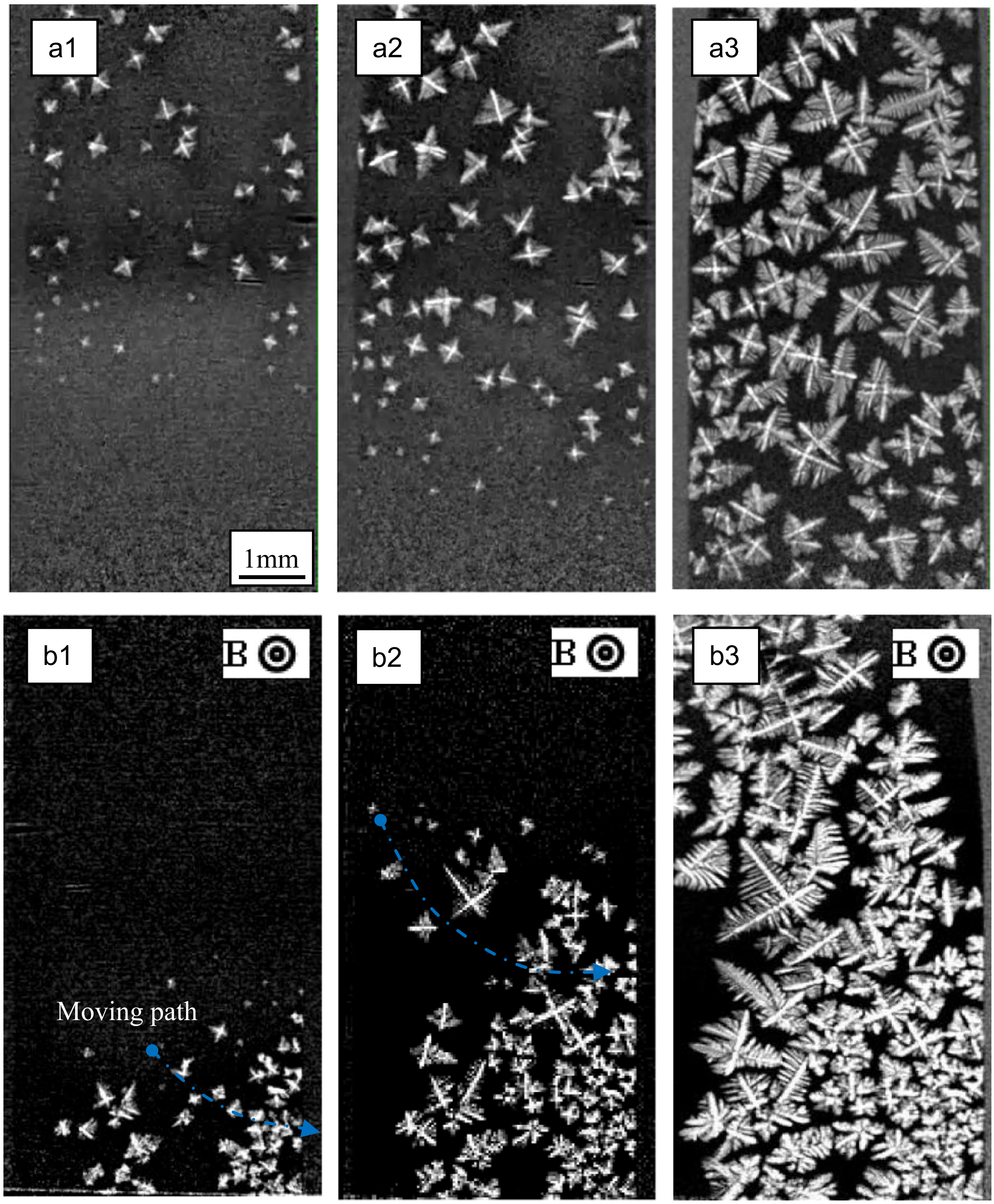

Fig. 3. The successive *in-situ* Synchrotron X-ray images of the motion of the α-Al grains in directionally solidified Al-10wt.%Cu alloy without and with a 0.08T-magnetic field (G = 10 K/cm, cooling rates are the same that 2 K/min): (a1)–(a3) Successive images without no magnetic field; (b1)–(b3) successive images with the magnetic field [13].

The modification of the structure under the magnetic field should be attributed to the TE magnetic effects. Now, let us recall the TE magnetic effects during directional solidification under the magnetic field. In general, all materials during solidification exist thermal gradient along the heat flux direction and different material properties between liquid and solid phase. If the thermal gradient has a non-zero component along the liquid/solid interface, the TE currents appear at the liquid/solid interface [12]. Thus, the interaction between TE currents and the applied magnetic field will produce the TE magnetic force. Fig. 4(a) and (b) show numerical TE current and magnetic force on a spherical α-Al grain immersed in a liquid metal, respectively. A TE current appears both in liquid and solid phase, which induces a unidirectional TE magnetic force acting on the α-Al grain when a transverse magnetic field is applied. The amplitude of the TE magnetic force acting on the solid grain can be written as [14]:

$$F = 2\,\sigma_s\,G\,B_0\left[\frac{\sigma_l}{2\,\sigma_l + \sigma_s}\right](S_s - S_l)$$

where σ_s and σ_l respectively denote the electrical conductivity in solid and liquid; S_s and S_l respectively denote the TE power in solid and liquid. Moreover, due to the gravity force, the nucleated grains will tend to fall down and then form uniform structures, as shown in Fig. 4(d). When the magnetic field is applied, the moving path of

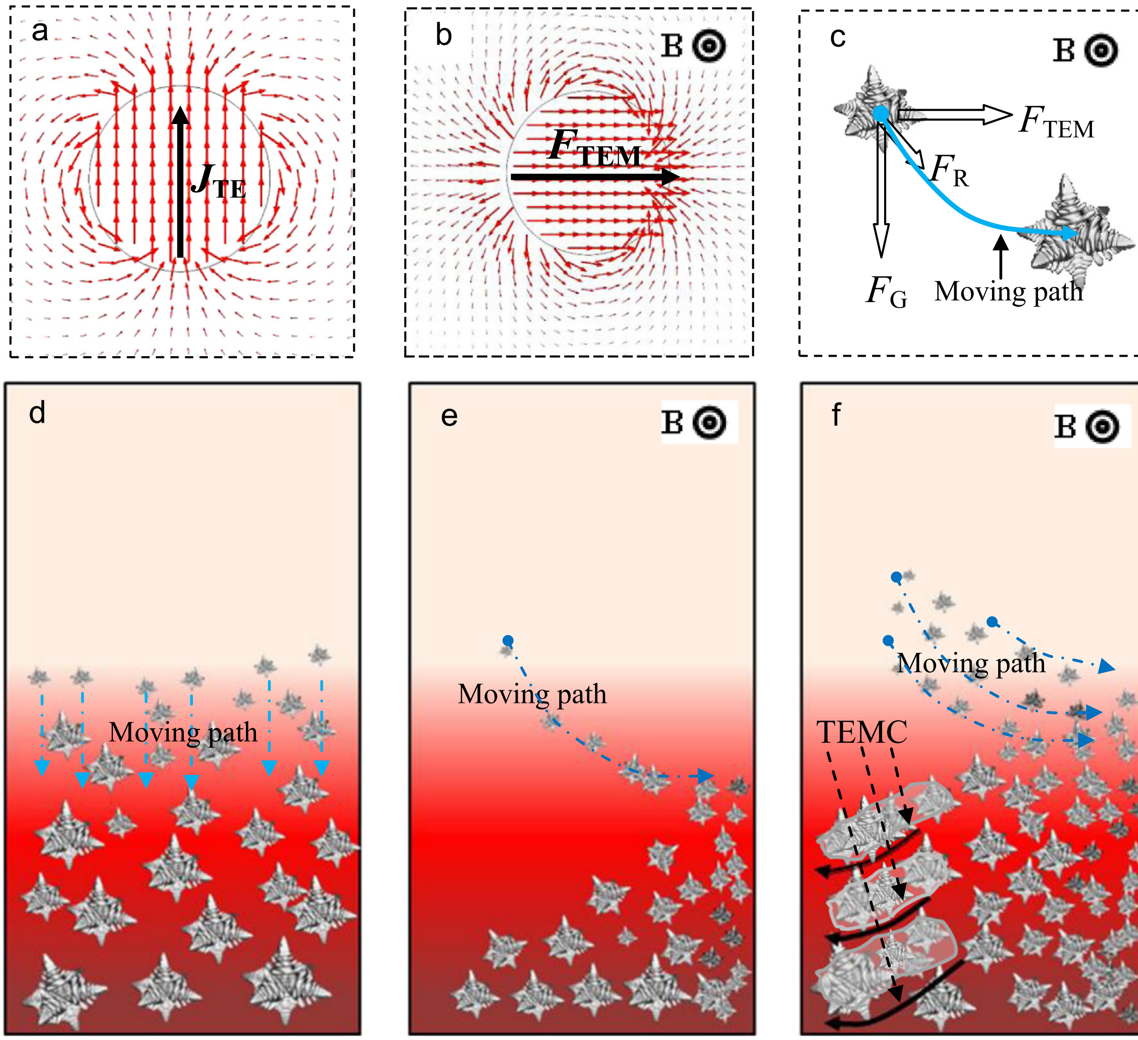

Fig. 4. Schematic view for the TE magnetic force and moving path of the α-Al grains during directional solidification under a transverse magnetic field: (a) and (b) Numerical TE current and TE magnetic force on the α-Al grains; (c) the forces acting on the α-Al grains and the moving path of the α-Al grains during directional solidification under a transverse magnetic field (FG: the gravity force, FTEM: the TE magnetic force and FR: the resultant force); (d) the moving path of the α-Al grains in the case of no magnetic field; (e) and (f) the moving path of the α-Al grains with a transverse magnetic field and the structures solidified.

the solid grain becomes parabolic curve due to the complex interaction between the TE magnetic force and the gravity, as shown in Fig. 4(c). As grains are moved to the right side of the sample under a transverse magnetic field, the number of the grains nucleated on this side of is larger. Generally, the more of the number of the nucleated grain, the smaller of the size of the grains in a certain volume. So, the number of grains nucleated on the right side of is larger, the size of the grains solidified on this side is smaller, as shown in Fig. 4(e) and (f). Moreover, the TEMC in the liquid remarkably affected the dendrite morphology during directional solidification and the related detailed description can be found in previous works [8]. Along with the decrease of the liquid fraction during the solidification process, the TEMC will be produced in the liquid, as shown in Fig. 4(f), which will cause the formation of the deflected dendrites (see Fig. 1 and Fig. 2).

Furthermore, the removal of inclusions from molten metal by means of the electromagnetic technologies is always a research hotspot [15–18]. The above experimental results show that the TE magnetic force can drive the movement of solid gains in molten metal. Thus the application of the TE magnetic force is capable of removing inclusion from molten metal. Fig. 5 shows the moving path of inclusion in molten metal during directional solidification under a transverse magnetic field. If the TE power of inclusion (S_i) is larger than one of the molten metal (S_m), the applied magnetic field will cause the inclusions to move towards the right side of the sample. Otherwise, the inclusion will be moved to the left side of the sample. Therefore, the TE magnetic force can be as an effective method to remove the inclusions from molten metal.

4. Conclusions

The effect of a transverse magnetic field on the growth of equiaxed grains during directional solidification of Al-10 wt% Cu alloys was investigated experimentally and numerically, and the obtained results are summarized as follows:

1. The application of the magnetic field significantly affected the size and distribution of equiaxed grains, which led to the appearance of the refined and coarsen equiaxed grains on the both sides of the sample, respectively.
2. *In-situ* synchrotron X-ray imaging shows that a transverse magnetic field can generate some force which can act on equiaxed grains and induce the movement of equiaxed grains during directional solidification.
3. Numerical results reveal that the TE magnetic effects may play a key role in the modification of the structure under the magnetic field.

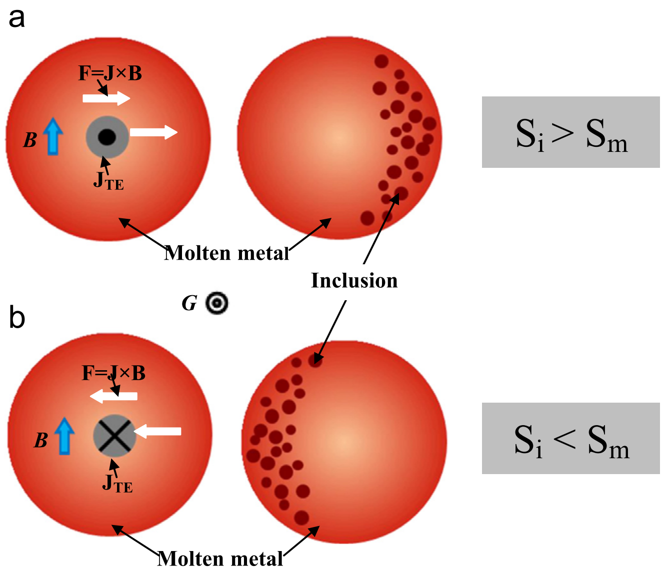

Fig. 5. Movement of inclusion in molten metal during directional solidification under a transverse magnetic field in two cases: (a) TE magnetic force acting on inclusion during directional solidification under a transverse magnetic field in the case of Si > Sm; (b) TE magnetic force acting on inclusion during directional solidification under a transverse magnetic field in the case of Si < Sm.

4. Further, a new method which can remove inclusions from molten metal is proposed by means of the TE magnetic force.

Acknowledgments

This work is supported partly by the European Space Agency through the Bl-inter 09_473220, National Natural Science Foundation of China (Nos. 51271109 and 51171106), and the Program for Professor of Special Appointment (Eastern Scholar) at Shanghai Institutions of Higher Learning.

References

[1] J.R. Carruthers, in: W.R. Wilcox, R.A. Lefever (Eds.), Preparation and Properties of Solid State Materials, vol. 3, MarcelDekker, New York, 1997, p. 1.
[2] D.H. Matheson, M.S. Wargo, D. Motakef, J. Carlson, A.J. Nakos, Cryst. Growth 85 (1987) 557.
[3] G.D. Robertson, D. O'Connor, J. Cryst. Growth 76 (1986) 100.
[4] W.J. Boettinger, F. Biancaniello, S. Coriell, Met. Mater. Trans. A 12A (1981) 321.
[5] S.N. Tewari, R. Shah, H. Song, Met. Mater. Trans. A 25A (1994) 1535.
[6] T. Alboussière, R. Moreau, D. Compte, Rendu de l'Acad. Sci. 313 (1991) 749.
[7] O. Laskar, Thesis, INPG, France, 1994.
[8] P. Lehmann, R. Moreau, D. Camel, R. Bolcato, Acta Mater. 46 (1998) 4067.
[9] X. Li, Z.M. Ren, Y. Fautrelle, A. Gagnoud, Y.D. Zhang, C. Esling, Scr. Mater. 60 (2009) 443.
[10] X. Li, Y.D. Zhang, Y. Fautrelle, Z.M. Ren, C. Esling, Scr. Mater. 60 (2009) 489.
[11] X. Li, A. Gagnoud, Y. Fautrelle, Z.M. Ren, R. Moreau, Y.D. Zhang, C. Esling, Acta Mater. 60 (2012) 3321.
[12] J.A. Shercliff, J. Fluid Mech. 91 (1979) 231.
[13] G. Salloum-Abou-Jaoude, J. Wang, L. Abou-Khalil, G. Reinhart, Z. Ren, N. Mangelinck-Noel, X. Li, Y. Fautrelle, H. Nguyen-Thi, J. Gryst. Growth 417 (2015) 25.
[14] J. Wang, Y. Fautrelle, Z.M. Ren, X. Li, H. Nguyen-Thi, N. Mangelinck-Noel, G. Salloum Abou Jaoude, Y.B. Zhong, I. Kaldre, A. Bojarevics, L. Buligins, Appl. Phys. Lett. 101 (2012) 251904.
[15] K. Takahashi, S. Taniguchi, ISIJ Int. 43 (6) (2003) 820.
[16] D. Shu, T. Li, B. Sun, J. Wang, Y. Zhou, Met. Mater. Trans. A 30A (1999) 2979.
[17] S.Q. Wang, L.F. Zhang, Y. Tian, Y.L. Li, H.T. Ling, Met. Mater. Trans. B 45B (2014) 1915.
[18] T. Ogasawara, N. Yoshikawa, S. Taniguchi, T. Asai, Met. Mater. Trans. B 35B (2004) 847.