Available online at www.sciencedirect.com

ScienceDirect

Acta Materialia 64 (2014) 367–381

Acta MATERIALIA

www.elsevier.com/locate/actamat

Effect of a weak transverse magnetic field on solidification structure during directional solidification

X. Li [a,b,*], Y. Fautrelle [b], A. Gagnoud [b], D. Du [a], J. Wang [a,b], Z. Ren [a], H. Nguyen-Thi [c,d], N. Mangelinck-Noel [c,d]

[a] Department of Material Science and Engineering, Shanghai University, Shanghai 200072, People's Republic of China
[b] SIMAP-EPM-Madylam/G-INP/CNRS, PHELMA, BP 75, 38402 St Martin d'Heres Cédex, France
[c] Aix Marseille University, Campus Saint-Jerome, Case 142, 13397 Marseille Cédex 20, France
[d] CNRS, IM2NP, Campus Saint-Jerome, Case 142, 13397 Marseille Cédex 20, France

Received 9 October 2013; accepted 23 October 2013
Available online 5 December 2013

Abstract

Six alloys were directionally solidified at low growth speeds (1–5 μm s^{-1}) under a weak transverse magnetic field ($\leqslant$0.5 T). The results show that the application of a weak transverse magnetic field significantly modified the solidification structure. Indeed, it was found that, along with the refinement of cells/dendrites, the magnetic field caused the deformation of liquid–solid interfaces, extensive segregations (i.e., freckles and channels) in the mushy zone, and a change in the mushy zone length. Further, in situ monitoring of the initial transient of the directional solidification was carried out by means of synchrotron X-ray radiography. It was observed that dendrite fragments and equiaxed grains were moved approximately along the direction perpendicular to the magnetic field. This result shows that a thermoelectric magnetic force (TEMF) acted on the liquid or the solid during directional solidification under a weak magnetic field. The TEMF during directional solidification under a transverse magnetic field was investigated numerically. The results reveal that a unidirectional TEMF acted on the solid and induced thermoelectric magnetic convection (TEMC) in the liquid. Modification of the solidification structure under a weak magnetic field is attributed to TEMC-driven heat transfer and interdendritic solute transport and TEMF-driven motion of dendrite fragments.

Keywords: Transverse magnetic field; Directional solidification; Solidification structure; Synchrotron radiation

1. Introduction

Solidification in a magnetic field is an interesting topic and has attracted much attention from researchers. However, the effect of a static magnetic field on solidification has not been well understood, mainly because the experimental observations were made in different configurations, such as ingot solidification or directional solidification. In ingot solidification, the magnetic field brakes the convection in the liquid and reduces the heat-transfer rate [1,2]. In directional solidification, the magnetic field also brakes the convection, but in directional solidification in the dendritic regime some unexpected behaviors are observed [3–7]. These behaviors depend on the composition of the alloy and the experimental conditions. Youdelis and Dorward [3,4] applied a 3.4 T transverse field on the directionally solidified Al–Cu alloy. The result showed that the value of the effective partition coefficient decreased with the presence of the field, as if the magnetic field enhanced mass transport in the liquid. Tewari et al. [5] found that the cellular array was severely distorted, and stripes of freckles on the plane perpendicular to the magnetic field formed when a Pb–Sn alloy was solidified vertically at very low growth speeds under a 0.45 T transverse magnetic field. The experiment were performed by Alboussière et al. [6] and Lakar [7] on Bi–60 wt.% Sn and Cu–45 wt.% Ag alloys, solidified

* Corresponding author at: SIMAP-EPM-Madylam/G-INP/CNRS, PHELMA, BP 75, 38402 St Martin d'Heres Cédex, France.
E-mail address: lx_net@sina.com (X. Li).

1359-6454/$36.00 © 2013 Acta Materialia Inc. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.actamat.2013.10.050

vertically under solutally and thermally stabilizing conditions with a 0.6 T transverse or 1.5 T axial magnetic field. Large freckles appear in this case, showing that a new movement has been created. Alboussière et al. [6] suggested that this new flow was induced by the interaction between the magnetic field and thermoelectric (TE) effects. Subsequently, Lehmann et al. [8] offered some experimental evidence for thermoelectromagnetic convection (TEMC).

Regarding the forces induced by magnetic fields, three extra forces in the liquid as well as the solid may normally be introduced under the magnetic field. One is the magnetic force arising from the interaction of the magnetism of a

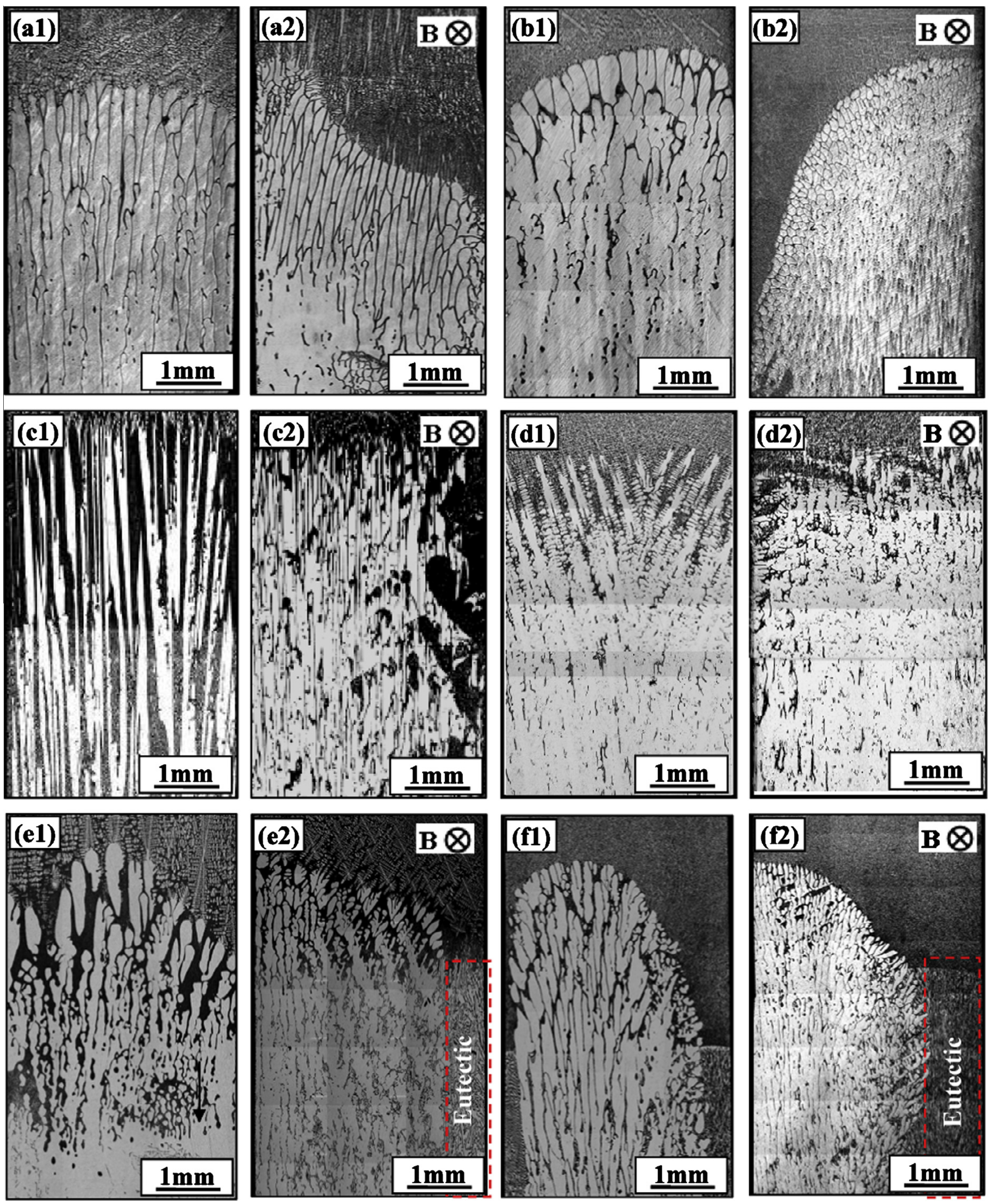

Fig. 1. Microstructures near the liquid–solid interface in six directionally solidified alloys both without and with a 0.5 T transverse magnetic field: (a) Al dendrite in Al–2.5 wt.% Cu alloy, 5 μm s^{-1}; (b) Sn dendrite in Sn–20 wt.% Bi alloy, 1 μm s^{-1}; (c) Al_2Cu dendrite in Al–40 wt.% Cu alloy, 2 μm s^{-1}; (d) γ dendrite in DZ417G Ni-based superalloy, 5 μm s^{-1}; (e) Al dendrite in Al–7 wt.% Si alloy, 2 μm s^{-1}; (f) Sn dendrite in Sn–20 wt.% Pb alloy, 1 μm s^{-1}.