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Melting and solidification: processes and models/Processes and control of crystal growth

Control of melt convection by a travelling magnetic field during the directional solidification of Al–Ni alloys

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Abstract

In the field of the metallic alloy development, the main industrial goals are the control of the metallurgical structure and defects. Hydrodynamic movements in the liquid phase have a significant influence on properties of the solidified product.

We focus our attention on two major effects influenced by forced convection induced by a travelling magnetic field: the macrosegregation and the grain structure for Al-3.5 wt% Ni alloys. We show that this configuration can control macrosegregations and that, moreover, the dendritic primary spacing maybe modified by varying the applied field.

With regards to the grain structure, we exhibit the effect of the forced convection on the microstructure. For the equiaxed regime growth, the effect of the travelling magnetic field on the constitutional undercooling and on the refiner distribution induces an equiaxed to an elongated transition. This mechanism enhances the nucleation and the growth of equiaxed grains. In the case of non-refined alloys, a mode of elongated free grains is obtained most likely because of fragmentation. ***To cite this article: K. Zaïdat et al., C. R. Mecanique 335 (2007).***

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Résumé

Influence d'un champ magnétique glissant sur la solidification dirigée des alliages métalliques binaires. Dans le domaine de l'élaboration des alliages métalliques, les principaux enjeux industriels résident dans la possibilité de maîtriser la structure métallurgique ainsi que les défauts qui surviennent lors de la phase de solidification. Lors de la solidification, les mouvements hydrodynamiques dans la phase liquide ont une influence importante sur les propriétés du produit solidifié.

Notre attention s'est portée sur deux effets majeurs influencés par la présence de convection forcée par champ magnétique glissant : la macroségrégation et la structure de grains pour un alliage d'Al-3,5pds% Ni en présence ou non de particules affinantes. Nous montrons que dans le cas de l'alliage choisi, la macroségrégation peut-être contrôlée et que de plus, l'espacement primaire dendritique est modifié en fonction du champ appliqué.

En ce qui concerne les structures de grains, nous montrons l'influence de la convection forcée sur le développement de la microstructure. Dans le cas d'une solidification de type équiaxe, l'influence de la convection forcée sur la couche solutale et sur la distribution des particules inoculantes montre une transition vers un régime de grains allongés. Dans le cas des alliages non affinés, un régime de grains libres allongés a pu être obtenu probablement à cause de la fragmentation. ***Pour citer cet article : K. Zaïdat et al., C. R. Mecanique 335 (2007).***

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Mots-clés : Mécanique des fluides ; Solidification dirigée ; Dendrites ; Grains colonnaires ; Équiaxe ; Champ magnétique glissant ; Convection naturelle et forcée

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1. Introduction

A better understanding of the formation of dendritic structures, whether columnar or equiaxed, and when or how they changes from the former to the latter, is crucial to tailor materials in a reproducible fashion during casting processes. The selection of these solidification patterns is controlled by the complex interplay of thermal, solutal, capillary and kinetic length or time scales. Our knowledge about the influence of natural or forced convection on microstructure development is rather limited. Convection results in interfacial morphologies that are potentially very different from those generated in purely diffusive transport conditions. Inversely, the evolving microstructure can also trigger unexpected and complicated flow phenomena in the melt. Convection plays an even more important role in equiaxed solidification and the columnar to equiaxed transition (CET), since not only the liquid moves, but both nuclei (resulting from fragmentation of dendrites arms or refining particles added to the melt) and growing crystals may be driven by the flow. Additionally, segregations left during the solid formation at different scales determine also the properties of the final material. Segregations are non-homogenous repartition of alloy elements inside the solid material. They appear at the scale of the dendrite (microsegregation), at the mesoscopic scale of several dendrites (freckles) and/or at the scale of the ingot (macrosegregation).

In the framework of the European program CETSOL (*Columnar to equiaxed transition in solidification processing*) we proposed to study the influence of an external force during the solidification processing. The main objective of these experiments is to improve the understanding of the phenomena induced by forced convection on the macrosegregations and on the grain structure. Solidification experiments are carried out with non-refined and refined Al–Ni 3.5 wt% alloys under natural convection or with different levels of forced convection by a travelling magnetic field (TMF).

2. Experimental setup and results

Directional solidification with the Bridgman technique is classically used to check models of microstructure and segregation formation by varying the three independent control parameters, i.e. concentration, temperature gradient and pulling rate. A Bridgman furnace named BATMAF (Bridgman Apparatus with Travelling Magnetic Field), with a possibility of applying a travelling magnetic field induced by a tubular linear motor, was designed for the solidification of aluminium-based alloys [1]. The TMF drives a simple forced flow in the liquid above the solidifying interface. Contrary to the rotating magnetic field, the TMF gives the possibility of creating meridional melt circulations directly, i.e., without the unnecessary forcing of a non-uniform rotational flow and to control the meridional flow direction (upward or downward).

Some experiments are achieved in an Al-3.5wt%Ni alloy non-refined or refined with 0.5 wt% of the conventional Al-5wt%Ti-1wt%B refiner introduced to enhance the equiaxed microstructure. The sample is contained in a boron nitride crucible where six thermocouples are placed on the outside walls in order to measure the temperature during the experiment. The sample dimensions are 8 and 150 mm for the internal diameter and the length, respectively. At the beginning, an imposed temperature gradient of 30 K/cm is applied; however, the application of the electromagnetic stirring modifies the temperature gradient during the solidification. In the following, the measured temperature gradient is given as parameter G for each experiment. After partial melting and a short stabilization, directional solidification is performed by pulling the sample at the same pulling rate for all experiments: 10 μm/s. Then, a quench is performed by pulling the sample at a rate of about 250 μm/s. The value given for the stirring intensity corresponds to the measured maximal field intensity and is noted B.

Transverse and longitudinal sections are then cut for metallographic examination. Microstructures are observed by conventional optical microscopy after simple polishing or anodisation to reveal the microstructure and the grain structure, respectively.

2.1. Influence on macrosegregations

Macrosegregation can be induced by thermosolutal convection, forced convection, solidification shrinkage, transport and sedimentation of grains, or deformation of the solid skeleton [2]. In the case of thermosolutal convection, the thermal and solutal buoyancy forces can either aid or oppose each other, depending on the direction of the thermal gradient and whether the rejected solute is denser compared to the solvant. For a thermally and solutely stable configuration for convection (e.g. vertical solidification and rejection of a denser solute in upwards solidification as Al-3.5wt%Ni), we expect to avoid thermosolutal convection. Nevertheless, in aluminium alloys because the solid and liquid thermal conductivities are different, a radial thermal gradient and thus radial convection exist at the level of the interface at low growth rates. This leads to a severe distortion of the front [3,4]. First, the rejected solute segregates at the periphery and the microstructure is localized at the centre (clustered microstructure) (Fig. 1(a)). Then, aluminium dendrite tips protrude markedly into the liquid phase with a eutectic front at the base of the solidification front (steepling phenomenon).

As mentioned above, the Lorentz force direction can be controlled to create two different fluid flow configurations. In the first configuration (downward case), the solute is transported from the periphery to the centre by the induced forced flow (Fig. 1(b)). This is the opposite direction compared to natural convection (in the case of an Al–Ni alloy). In this case, the solute is accumulated at the centre of the sample and gives birth to a segregated channel. This configuration produces a competition between the natural and the forced convection. However, it is worth noticing that there is a scaling difference between flows corresponding to natural and forced convection [5]. The natural convection produces a convection loop close to the mushy zone, whereas the forced fluid flow induces a convection loop at the scale of the sample. For a low magnetic regime with $B < 30$ mT, the natural convection is not negligible and it appears a non-centred segregated channel. Above 30 mT, a segregated channel is clearly observed at the centre of the sample (Figs. 2(c) and (d)) and has a stable position along the vertical direction. In this case, the solute is accumulated at the centre of the sample by forced flow which is dominant and gives birth to a segregated channel. Moreover, this channel drives a large amount of solute which leads to a more compact dendritic array at the periphery.

In upward configuration, the Lorentz force (from the bottom to the top near the crucible) induces a forced flow at the scale of the sample which transports the solute from the centre to the periphery (Fig. 1(c)). When increasing the electromagnetic field intensity, the thickness of the eutectic layer decreases (Figs. 2(a), (b)). Indeed, when the fluid flow velocity is increased, the solute has not enough time to deposit and the local concentration cannot reach the eutectic concentration to form a eutectic layer at the periphery. This induces a longitudinal macrosegregation at the end of the solidification instead of radial macrosegregation.

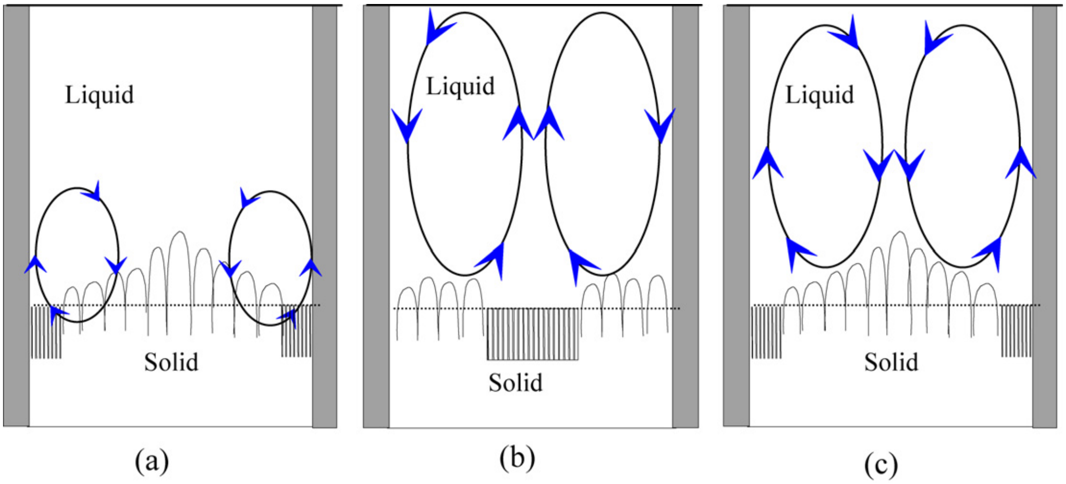

Fig. 1. Sketches of the fluid flow: (a) fluid flow induced by the natural convection; (b) forced fluid flow induced by an electromagnetic downward pumping force; and (c) forced fluid flow induced by an upward pumping force.

Fig. 1. Schéma de l'effet de la convection sur une structure de croissance colonnaire : (a) cas de la convection naturelle ; (b) convection forcée dans le sens opposé à la convection naturelle ; (c) dans le même sens.

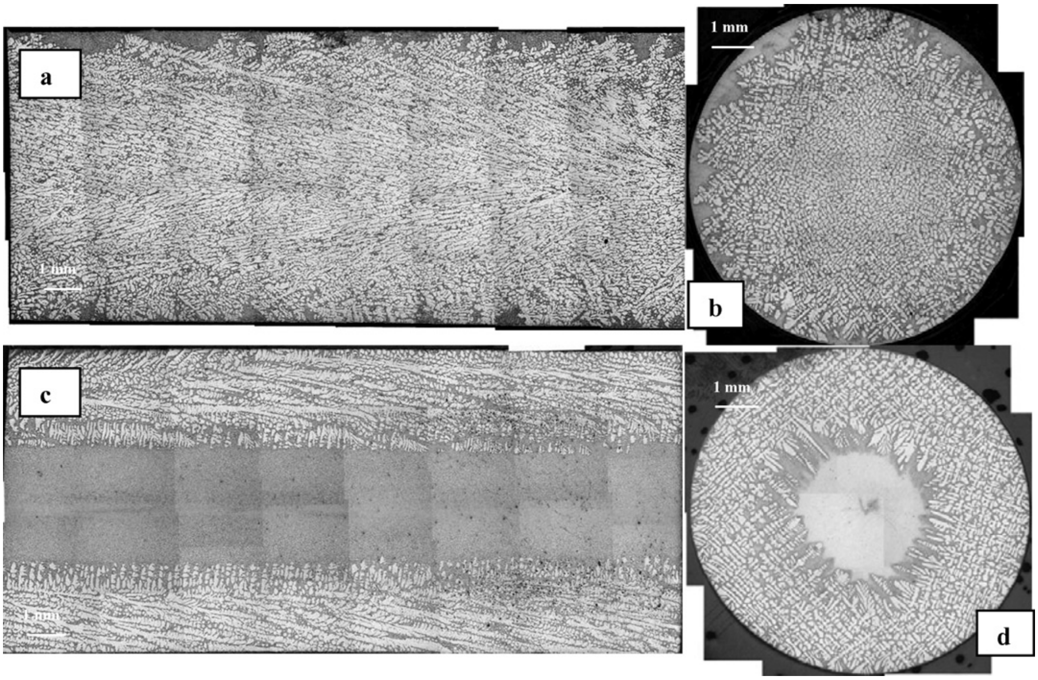

Fig. 2. Longitudinal and transverse cross-sections of an Al-3.5wt%Ni non-refined alloys solidified in a Bridgman furnace $V = 10\ \mu\text{m/s}$: (a), (b) downward configuration $B = 30$ mT, $G = 20$ K/cm; (c), (d) upward configuration $B = 45$ mT, $G = 18$ K/cm.

Fig. 2. Coupes longitudinales et transverses d'un alliage Al-3,5pds %Ni non affiné en présence d'un champ magnétique glissant. Cas d'une convection forcée dans le même sens (a), (b) et dans le sens opposé à la convection naturelle (c), (d).

Moreover, in this configuration, we observe a modification of the dendritic array, the primary arm spacing decreases when the stirring intensity is increasing as predicted by Lehman et al. [6]. The law obtained predicts a decrease of the primary arm spacing when the entering velocity intensity is increasing.

2.2. Influence on microstructure development

In the case of a refined alloy, equiaxed grains can nucleate or be initiated [7–9] on the refiner particles in the liquid above the columnar front. This condition can be fulfilled if the constitutional undercooled zone existing above the columnar front during its growth exceeds the nucleation undercooling. In the case of Al–Ni alloys, the partition coefficient is less than unity and the excess solute rejected from the solid accumulates in an enriched boundary layer ahead of the solidification front. The equiaxed microstructure is disturbed when one introduces a forced convection during the directional solidification, and the forced fluid flow washes the constitutional undercooling or influences the nucleation on the refining particles. On Figs. 3(a) to (c), we present the effect of the forced convection on the refining particles after solidifying of a refined alloy in two steps. First a few centimetres are solidified under a forced convection induced by a TMF around 45 mT. Then, we stop the forced convection. We observe a transition from an elongated to a columnar microstructure respectively in the region with solidified with TMF and without TMF. This result shows the effect of the forced convection on the refining particles, because at this solidification speed (10 μm/s) without TMF, we obtain an equiaxed structure. According to Greer [9], the size of the refining particles is an important parameter for heterogeneous nucleation, the biggest being more effective. Moreover during mixing, the particles are transported through the liquid bath but also through the mushy zone. It is then rather easy to imagine that particles of a size higher than a certain threshold, related to interdendritic spacing, are blocked in the secondary arms of dendrites, whereas the smallest (less effective according to Greer [9]) would be transported in the liquid bath. One could speak then about a 'filtering effect' by the mushy zone for the refining particles.

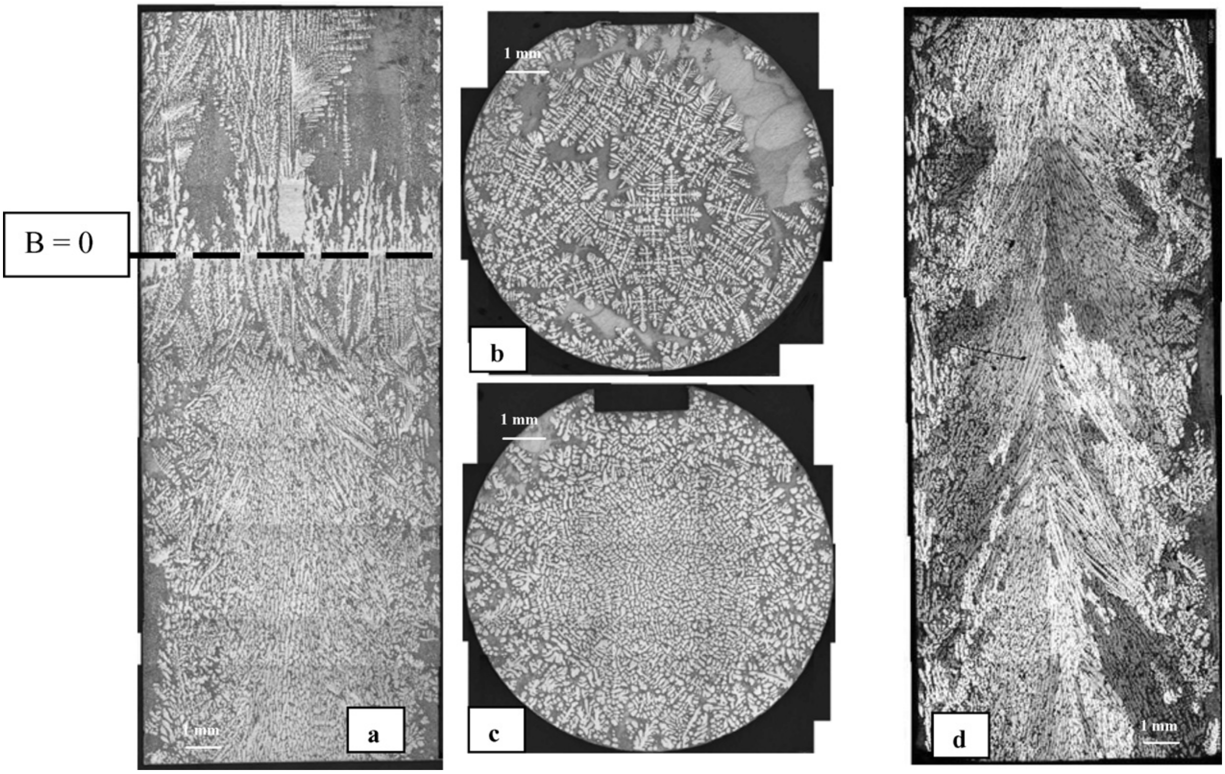

Fig. 3. Longitudinal and transverse cross-sections of an Al-3.5wt%Ni refined and non-refined alloys solidified in a Bridgman furnace $V = 10\ \mu\text{m/s}$: (a) refined alloy ($B = 45$ mT and $B = 0$ mT, $G = 20$ K/cm); (b) refined alloy ($B = 45$ mT, $G = 20$ K/cm); (c) refined alloy ($B = 0$ mT, $G = 28$ K/cm); and (d) non-refined alloy ($B = 30$ mT, $G = 20$ K/cm).

Fig. 3. Coupes longitudinales et transverses d'Al-Ni3,5%pds solidifié dans un four Bridgman à $V = 10\ \mu\text{m/s}$: (a) Alliage affiné ($B = 45$ mT and $B = 0$ mT, $G = 20$ K/cm) ; (b) Alliage affiné ($B = 45$ mT, $G = 20$ K/cm) ; (c) Alliage affiné ($B = 0$ mT, $G = 20$ K/cm) ; et (d) Alliage non affiné ($B = 30$ mT, $G = 20$ K/cm).

An elongated microstructure is obtained for a given range of field intensity when applying a travelling magnetic field in non-refined and refined alloys as shown in Figs. 3(a) and (d). In the case of non-refined Al–Ni alloys (Fig. 3(d)), the electromagnetic field seems to be able to create fragments, then these fragments grow in an environment controlled by the forced flow creating this typical elongated grains also observed with refiners.

3. Conclusion

Experiments with forced convection, induced by a travelling electromagnetic field, clearly reveal the effect of convection on the development of the microstructure and on the macrosegregations. This study is a very good example in that it shows that grain structure and segregation are linked and need to be studied concomitantly. In practise, we have seen that the travelling magnetic field can favour the dendrites fragmentation (non-refined alloys) and that the grain structure can be controlled by the application of travelling magnetic field by controlling its intensity and direction. So far, the effect of forced convection can only be superimposed onto the effect of natural convection. It is thus not possible to clearly show the independent effects of natural and forced convections. For these reasons, the experiments are programmed to take place on board the International Space Station (CETSOL, IMPRESS projects) using microgravity conditions i.e. without sedimentation phenomena and without natural convection.

Finally, we have shown that macrosegregation and grain structure can be controlled using a travelling magnetic field. More complex TMF profiles could be devised to improve the control of the CET and gain a better understanding of this phenomenon in presence of forced convection.

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