8th. World Congress on Computational Mechanics (WCCM8)
5th European Congress on Computational Methods in Applied Sciences and Engineeering (ECCOMAS 2008)
June 30 –July 5, 2008
Venice, Italy

Effects of Magnetic Fields on Crystal Growth

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Key Words: *Dendritic Growth, Magnetohydrodynamics, Multiphyics Problems, Modelling.*

ABSTRACT

The effects of a constant uniform magnetic field on thermoelectric currents during dendritic solidification were investigated using an enthalpy based numerical model. It was found that the resulting Lorentz force generates a complex flow influencing the solidification pattern.

Experimental work of material processing under high magnetic field conditions has shown that the microstructure can be significantly altered. There is evidence that these effects can be atrtributed to the Lorentz force created through the thermoelectric magentohydrodynamic interactions.[1,2] However the mechanism of how this occurs is not very well understood. In this paper, our aim is to investigate the flow field created from the Lorentz force and how this influences the morphology of dendritic growth for both pure materials and binary alloys.

The enthalpy based method is a front tracking method using a coarse mesh compared to other phase field methods. Finite difference approximations are used to calculate the curvature, interface speed, interface orientation and thermoelectric currents. Navier-Stokes equation provides a velocity field in the liquid fraction which is used to calculate the transport of the temperature and solute fields. This leads to two-way-coupling of the flow and the liquid fraction. Using a sub-stepping technique the full transport equation is not solved everytime step reducing the simulation time, while minimising the inheritted errors. The current density J is derived from the electric potential, requires a boundary condition to be placed at the solid/liquid interface. A submeshing technique is implemented on cells close to the interface to give a better approximation of the electric potential.

The system begins in a meta stable state with a non-dimensional temperature of -0.65 and the domain size is 1000x1000. At $t = 0$ a solid seed is placed in the domain and solidification proceeds. Using a finite difference enthalpy based method the subsequent growth is calculated. The first case looks at a stagnant liquid with no magnetic field. The crystal shows clear 4-fold symmetry and the tip velocity converges to a constant in line with microscopic solvability theory.[3] The thermoelectric current is derived by resolving the electric potential field. The current emanates from the tip and crosses the interface at the root of a fully developed dendrite.

In the presence of a constant external convection (fig 1) the transport of the temperature and solute fields causes the interfacial temperature and solute gradients to change the growth potential. In this case the

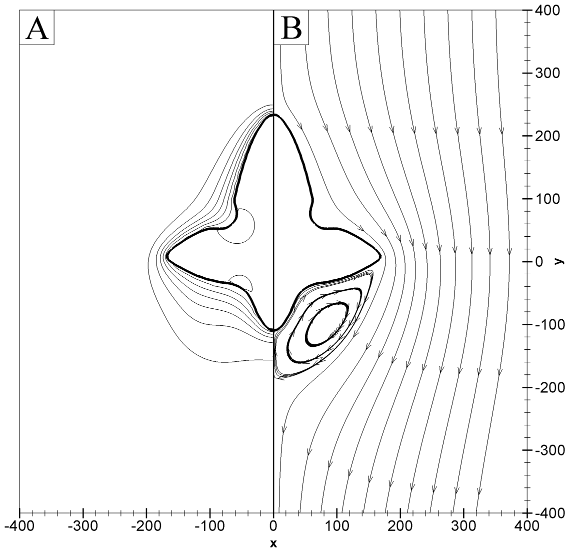

Fig. 1: Single crystal growth with an external convection at $t = 1000$. A: The Temperature field from $T = -0.65$ in the bulk to $T = 0$ in the solid. B: The Velocity streamlines.

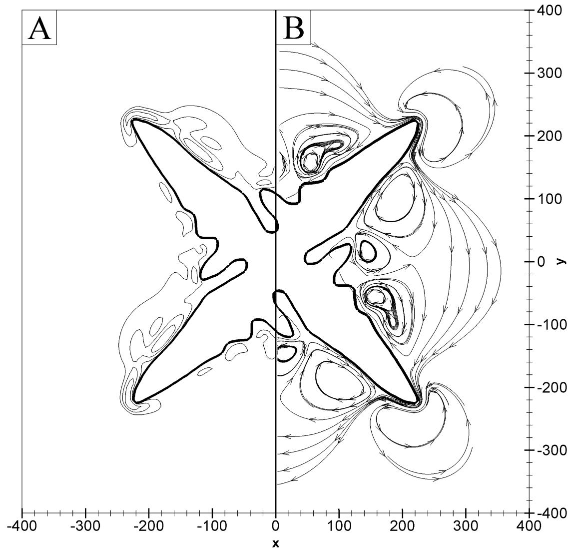

Fig. 2: Single crystal with magnetic field at $t = 1200$. A: The Velocity field, the maximum is at the interface with $V \sim 0.4$. B: The Velocity streamlines.

flow is directed on to the north tip causing an increased tip velocity, while the other tips are suppressed. The recirculation at the south tip is a result of a linear Darcy term ensuring that at $f = 0$, $V = 0$ resulting in a non slip zero velocity boundary condition imposed at the interface.

When a constant perpendicular external magnetic field is applied from the onset of solidification (fig2) stagnation points occur on the clockwise side of the arms, where the small perturbation of the temperature and solute gradient can initiate secondary dendrite growth. For the case of no magnetic field there are no secondary tips and the model does not include artifial stochatic perturbations. The secondary tips also have a local current density that is comparable to the primary dendrite tips influencing the local Lorentz force. The anti-clockwise side arms is the converse as the flow is pushed away from the arm lowering the interfacial thermal gradient and free energy thus stunting the secondary growth. A global recirculation also exists in the sense of the Lorentz force at the tip.

The effects of multiple interacting crystals and the resulting flow field is also investigated and it is found that small thermoelectric currents and residual momentum causes a a flow to still exist in the liquid regions between crystals. The effects of the Lewis number and varying magnetic field stengths will also be discussed.

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