INTRODUCTION

The work outlined here describes the development of two macroscopic models for the prediction of texture evolution during Bridgman furnace experiments that use cylindrical shaped samples. The first model employs a 2D axisymmetric thermal model coupled to a front tracking algorithm for modelling the evolution of axial and radial columnar grains. The second model employs a 1D thermal model (suitable for small sample diameters) with axial columnar mush front tracking; equiaxed growth is analytically modelled using the Avrami’s extended volume concept. Both models are demonstrated for typical experimental test case scenarios, specially, traditional Bridgman furnace solidification and power down solidification.

2D AXISYMMETRIC BRIDGMAN FURNACE FTM FOR COLUMNAR GROWTH

Thermal Model

\[ \frac{\partial T}{\partial t} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial T}{\partial r} \right) - \frac{\partial}{\partial z} \left( \alpha(z) \frac{\partial T}{\partial z} \right) \]

Temperature evolution in the domain is governed by the following heat transfer equation:

This equation was solved coupling a finite volume method [1] to a front tracking algorithm [2] for the evolution of the columnar dendrites region.

Front Tracking Model

- pulling velocity \( u \)
- dendrite tip growth velocity \( u_T = C_{VT} - T^n \)
- active markers
- non active markers, nucleate if \( T_T - T \geq \Delta T_{nucleate} \)
- \( u_T \) at time \( t \)
- \( \Delta T_T / \Delta t \) at time \( t + \Delta t \)

Simulations set-up

<table>
<thead>
<tr>
<th>SAMPLE</th>
<th>( T_0 )</th>
<th>( T_{min} )</th>
<th>( T_{max} )</th>
<th>( T_{end} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-45Al-5Cr-5Mo-2Zr-2B</td>
<td>1050°C</td>
<td>1450°C</td>
<td>1550°C</td>
<td>1550°C</td>
</tr>
</tbody>
</table>

The following figures show the solution at different time steps. The upper half of each plot shows the distribution of \( T \) in the sample, while the lower half shows the distribution of \( u_T \).

Discussion

- The columnar front moved to the left maintaining a convex shape, due to positive radial thermal gradient. No radial columnar growth occurred.

Power Down:

- The columnar front started to advance, and its shape became gradually concave, due to the reversal of the radial thermal gradient in the heater zone.
- When the nucleation undercooling at the sample circumference was reached, nucleation and radial columnar growth occurred.
- For the same length of the axial columnar zone (given by the position of the axial marker), radial columnar growth was more significant when a higher cooling rate was applied (S2).

1D AXISYMMETRIC BRIDGMAN FURNACE FTM FOR COLUMNAR GROWTH WITH AVRAMI-BASED EQUAISED GROWTH MODEL

Thermal Model: Numerical and Analytical

\[ \frac{dN}{dt} \]

Spherical equiaxed grain envelopes

The Extended Volume \( V_{eq} \) is the sum of all equiaxed shape envelopes, regardless of any geometric overlapping.

\[ V_{eq} = \int V_{eq} \, dN \]

However, the Avrami equation (below) accounts for impingement based on the assumption of homogeneous probability of nucleation events in all undisturbed areas.

\[ V_{eq} = V_{eq,0} (1 - e^{-k\tau}) \]

- The proposed model builds on an existing FTM [*] for columnar growth in a Bridgman furnace by introducing an equaised growth model.
- Nucleation of equaised grains is based on the ‘free growth’ model of Greer [*] where a lognormal distribution of inoculant particle diameter is assumed and related directly to get the nucleation undercooling, \( \Delta T_N \).
- Growth of the equaised mush envelope is modelled using the Avrami extended volume concept. The transformed volume fraction of equaised mush, \( \zeta \), is calculated ahead of the columnar front.
- A simulation of a power down scenario is carried out where a cooling rate of \( 5 \text{K/min} \) is applied. The model can be used to estimate columnar to equaised transition (CET) by defining a blocking fraction, \( \zeta_{blocking} \).
- It was found that at high seed density, \( N_s \), the position the CET position reaches a lower limit of approx. 122 mm, in the given test scenario.

Discussion

- The extended model is shown for power down and CET, where the CET position reaches a lower limit when seed particle density is increased. It is intended, in the future, to implement the analytical equaised growth model into the 2D axisymmetric model.

CONCLUSION

Firstly, the work outlines the development of a 2D axisymmetric model for heat flow in cylindrical samples directionally solidified in a Bridgman furnace; columnar dendritic growth is simulated using a front tracking method. The model is not restricted to low Biot number (<0.1) cases and, therefore, is useful where radial temperature gradients play an important role in microstructure development. The model is demonstrated by simulating traditional Bridgman solidification of a multicomponent Ti-Al alloy followed in series by power down solidification.

Secondly, the work outlines how an analytical equaised growth model, based on the Avrami extended volume concept, can be implemented in a similar 1D axisymmetric front tracking Bridgman furnace model. A lognormal distribution of nucleation undercooling is assumed. The model is used to simulate CET in a notional power down scenario. It is demonstrated that the CET position reaches a lower limit when seed particle density is increased. It is intended, in the future, to implement the analytical equaised growth model into the 2D axisymmetric model.

Bibliography


This work was carried out as part of the GRADECET (Graded Density of Columnar to Equaised Transition in Ti-Al alloys) and CETSOL (Columnar to Equaised Transition in SOLification Processing) microgravity application promotions, and the with the financial support of the European Space Agency PRODEX Programme (contract C1400010538S and C1400010713J2) under the management of the Irish delegation to ESA within Enterprise Ireland.