EQUIAXED DENDRITIC SOLIDIFICATION EXPERIMENT (EDSE)

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OBJECTIVES

The objective of the research is to quantitatively determine and understand the fundamental mechanisms that control the microstructural evolution during solidification of an assemblage of equiaxed dendritic crystals. A microgravity experiment will be conducted to obtain benchmark data on the transient growth and interaction of up to four equiaxed crystals of a pure and transparent metal analog (succinonitrile, SCN) under strictly diffusion dominated conditions. Of interest in the experiment are the transient evolution of the primary and secondary dendrite tip speeds, the dendrite morphology (i.e., tip radii, branch spacings, etc.) and solid fraction, the tip selection criterion, and the temperature field in the melt for a range of initial supercoolings and, thus, interaction "strengths" between the crystals. The experiment thus extends the microgravity measurements of Glicksman and coworkers for steady growth of a single dendrite [Isothermal Dendritic Growth Experiment (IDGE), first flown on USMP-2] to a case where growth transients are introduced due to thermal interactions between neighboring dendrites – a situation more close to actual casting conditions. Corresponding earth-based experiments will be conducted to ascertain the influence of melt convection. The experiments are supported by a variety of analytical models and numerical simulations. The data will primarily be used to develop and test theories of transient dendritic growth and the solidification of multiple interacting equiaxed crystals in a supercooled melt.

NEED FOR MICROGRAVITY

Experimental validation of present equiaxed dendritic solidification models is very limited, with only a few bulk solidification experiments conducted (on earth) using metal alloys [1]. There are basically four issues that have hampered the testing of such models: (i) the inability to control and quantify nucleation, (ii) the presence of uncontrolled, gravity-driven melt convection and crystal movement, (iii) the difficulty to observe growth in metallic systems, and (iv) the complications associated with coupled thermal and solutal undercoolings when using alloys. The Equiaxed Dendritic Solidification Experiment (EDSE) is designed to be simple, yet overcomes all of these limitations. In particular, even with an initially isothermal sample, gravity-driven convection caused by latent heat release can only be minimized in a microgravity environment. Due to our inability to analyze solidification microstructure evolution in the presence of this convection, it is important to first generate benchmark data for the diffusion limit.

RESULTS

The research to date has concentrated on:

(i) development of the science requirements for the proposed microgravity experiment;

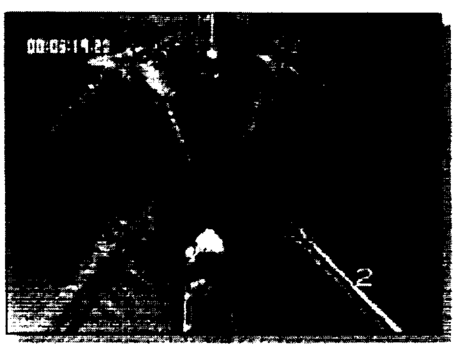
(ii) design, construction, and testing of a ground-based version of the experiment;

(iii) modeling of the growth of an assemblage of equiaxed dendritic crystals.

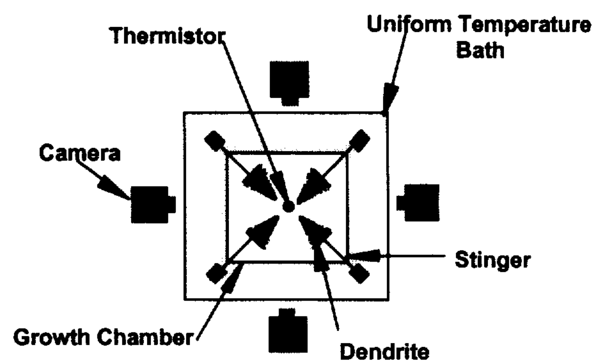
These efforts have culminated in the passing of the Science Concept Review (SCR) held at Nasa Lewis in February of 1998. The research team is now preparing for the Requirements Definition Review (RDR). Some of the experimental and theoretical research is described in greater detail below.

Ground-Based Experiments

We have conducted preliminary experiments involving an assemblage of equiaxed crystals using a setup that is functionally similar to the planned EDSE. A schematic of the setup together with a photograph taken during an experiment is shown in Figure 1.



Tetrahedron Arrangement of Dendrites



Dendritic Solidification Apparatus

Fig.1 Schematic of the equiaxed dendritic solidification apparatus and a photograph showing the tetrahedron arrangement of the dendrites

A glass growth chamber is contained within a temperature regulated bath. Four CCD cameras, with light sources, provide orthogonal images from four sides. The growth chamber contains pure SCN, several thermistors, and four stingers on which the dendrite growth is initiated. The tips of the stinger tubes are located at the corners of a tetrahedron with edge lengths, and hence spacing between the tips, of 10 mm. Thermoelectric coolers are mounted on the stinger ends opposite to the tips. An experiment starts by melting the SCN, then cooling the liquid to establish the desired supercooling in the growth chamber. The thermoelectric coolers are initiated and, after some time, dendrites start to emerge at the stinger tips. Although the present setup does not yet allow for a quantitative evaluation of the growth phenomena, we have performed image analysis in order to demonstrate some of the measurement techniques. We have also used this setup to examine numerous issues regarding the design of the planned microgravity experiment, including dendrite initiation, imaging requirements, stinger design, and others. We have clearly established the feasibility of the proposed experiment and measurement techniques.

Modeling

The proposed microgravity experiment is supported by several modeling efforts, that are not only intended to provide the theories that will be tested using the microgravity data, but will also be used to simulate the experiment. Work has concentrated on the development of four models:

(i) Modified Ivantsov Theory

A modification to the Ivantsov theory describing the heat flow around a dendrite tip has been proposed that takes into account the presence of other dendrites at a finite distance. This theory relies on the presence of a quasi-steady growth regime and the validity of the usual tip selection criterion. Figure 2 shows the predicted effect of interactions on the growth Peclet number for SCN and four crystals. By measuring the variation of both the tip velocity and radius in the planned microgravity experiment it will be possible to verify this theory.

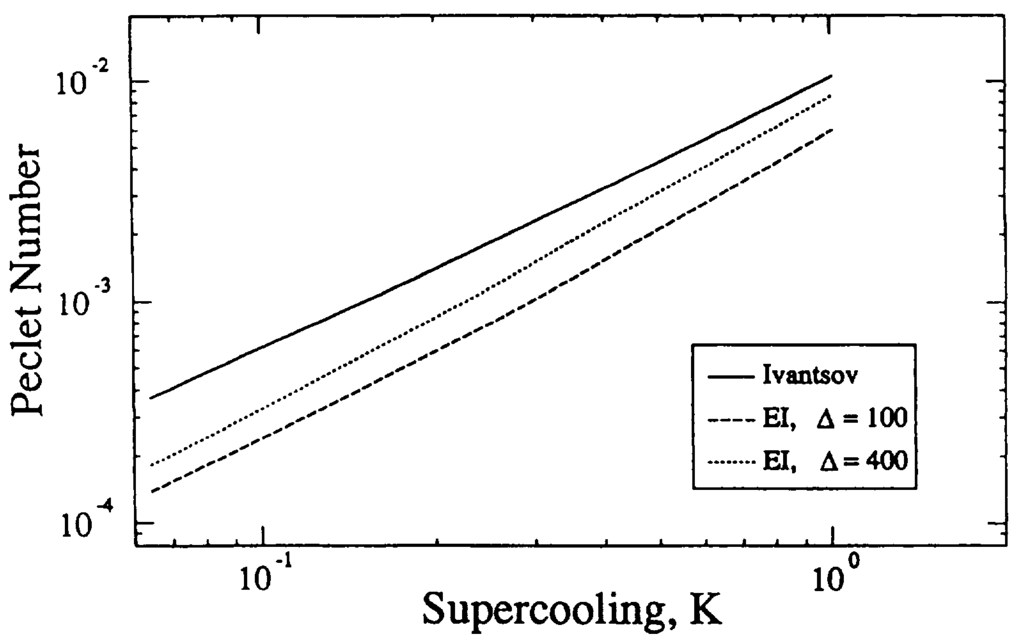
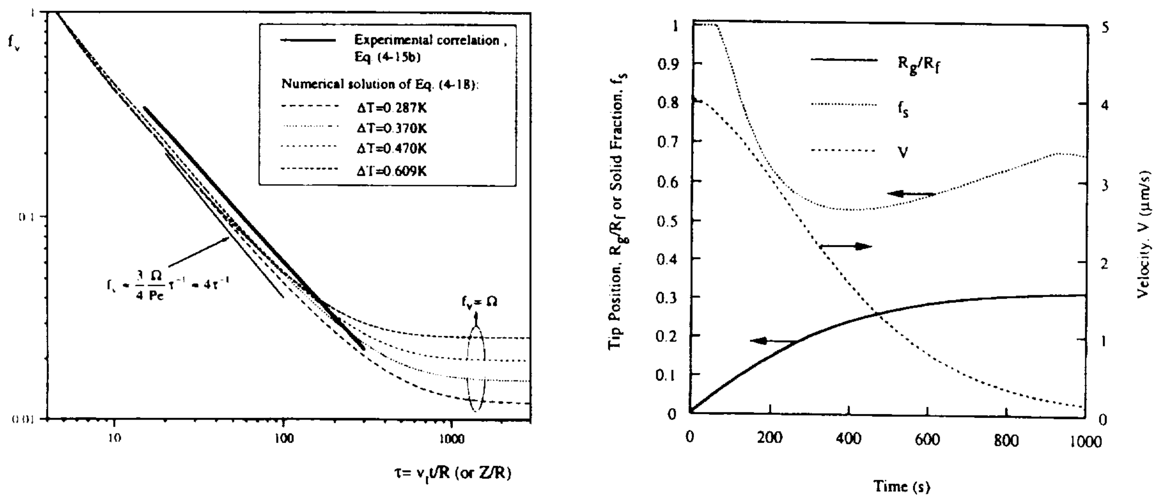


Fig. 2 Modified Ivantsov theory (EI): predicted effect of the dendrite proximity parameter, Δ, on the Peclet number-supercooling relation for an assemblage of four equiaxed crystals (SCN); the solid line is for an infinitely large proximity parameter (no interactions).

(ii) Modified Unit-Cell Model

We have developed a modified unit-cell model for predicting the internal solid fraction evolution in equiaxed dendritic solidification. Such unit-cell models can be used as micro-models in simulations of casting processes. While the original model for a single crystal was recently verified using data from the IDGE (Figure 3a) [2], the modified model is designed for an assemblage of multiple crystals and will be validated using EDSE data. As shown in Figure 3b, it predicts a transient variation in the tip speeds, as well as a transition from a fully dendritic structure to a more globulitic structure with increasing thermal interaction.



(a) (b)

Fig. 3 Unit-cell model: (a) predicted evolution of solid fraction for a single dendrite and comparison with IDGE data [2]; (b) predicted evolution of solid fraction, tip position, and tip velocity for an assemblage of equiaxed crystals (initial supercooling is 0.2K, SCN).

(iii) Mesoscopic Model

In this model [3, 4], the thermal interactions between the equiaxed crystals are fully accounted for by numerically calculating the three-dimensional, transient temperature field in the supercooled melt. The shape evolution and crystallographic orientation of the crystal envelopes are calculated by linking the numerical solution with a local analytical solution for the dendrite tip speeds. The mesoscopic model was validated for the steady growth of a single crystal using IDGE data. The full model is used to establish the requirements and parameters for the planned EDSE. Ultimately, we also plan to use the model to simulate the microgravity tests, in order to quantify the thermal field in the growth chamber and to test the validity of the local analytical solution under transient growth conditions. An example of simulation results for multiple equiaxed crystals is shown in Figure 4. Presently, the simulations are limited to diffusion dominated (microgravity) conditions.

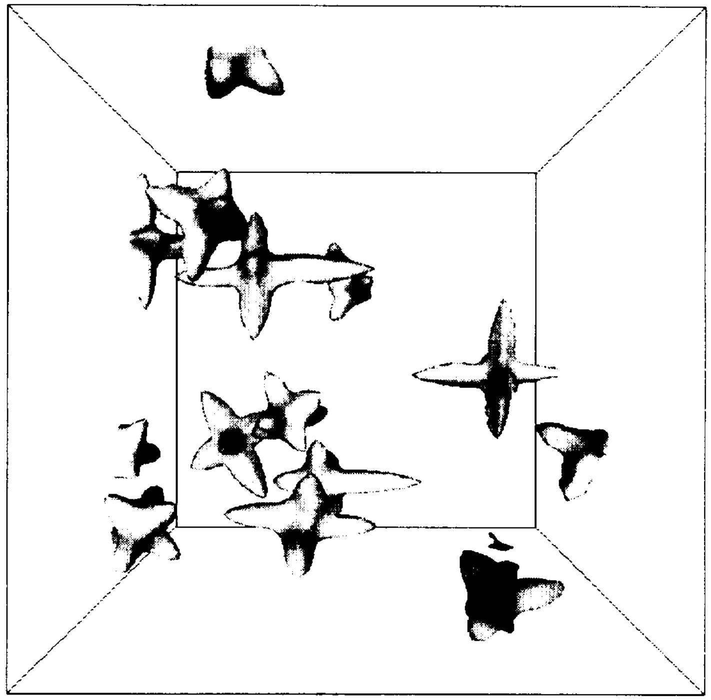


Fig. 4 Simulation results for the growth of multiple equiaxed crystals using the mesoscopic model; shown are the dendrite envelopes at an intermediate growth time (SCN, supercooling is 0.4K).

(iv) Phase-Field Model

We have also performed direct numerical simulations on a microscopic scale using the phase-field model [5, 6] to study the growth interactions of equiaxed dendrites and the resulting transients in the dendrite tip speeds and radii. An example of such simulations is shown in Figure 5. While simulations cannot yet be achieved for the conditions of the planned experiment, they do provide fundamental insight into issues such as dendrite tip operating point selection in the presence of growth interactions and transients.

REFERENCES

[1] Beckermann, C., "Modeling Segregation and Grain Structure Development in Equiaxed Solidification with Convection", Journal of Metals, Vol. 49, No. 3, March, 1996, pp. 13-17.

[2] Li, Q., and Beckermann, C., "Scaling Behavior of Three-Dimensional Dendrites", Physical Review E, Vol. 57, 1998, pp. 3176-3188.

[3] Steinbach, I., Kauerauf, B., Beckermann, C., and Guo, J., "Modeling of the Growth and Interactions of Equiaxed Dendrites on a Mesoscopic Scale", in Solidification 1998, eds. S.P. Marsh et al., TMS, Warrendale, PA, 1998, pp. 5-14.

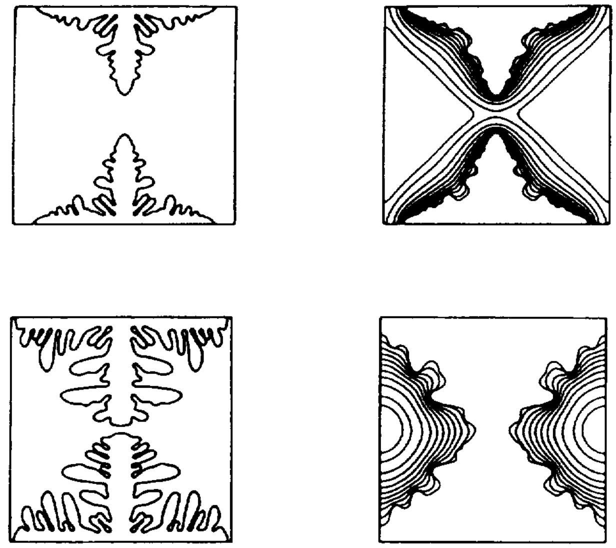


Fig. 5 Example of a phase-field simulation of two interacting equiaxed dendrites growing towards each other (left panels: phase-field contours, right panels: isotherms).

[4] Steinbach, I., Kauerauf, B., Beckermann, C., Guo, J., and Li, Q., "Three-Dimensional Modeling of Equiaxed Dendritic Growth on a Mesoscopic Scale", MCWASP VIII, eds. B.G. Thomas and C. Beckermann, TMS, Warrendale, PA, 1998, pp. 573-580.

[5] Diepers, H.J., Beckermann, C., and Steinbach, I., "A Phase-Field Method for Alloy Solidification with Convection", in Solidification Processing 1997, eds. J. Beech and H. Jones, Dept. Engineering Materials, The University of Sheffield, Sheffield, UK, 1997, pp. 426-430.

[6] Tong, X., Beckermann, C., and Karma, A., "Phase Field Simulation of Dendritic Growth with Convection", MCWASP VIII, eds. B.G. Thomas and C. Beckermann, TMS, Warrendale, PA, 1998, pp. 613-620.