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"The Influence of a Microgravity Environment on the Dendritic Morphology During Directional Solidification of Hypoeutectic Al-Si Alloys"

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Report Summary

NASA grant NAGW-2540 provided the opportunity to evaluate and extend ongoing studies of directionally solidified Al-Si alloys. Microstructural development was further characterized in terms of solidification processing parameters; novel relationships between processing and development of dendrite trunk diameters and tertiary dendrite arm spacings were found. This has resulted in three publications (one in print, one in press, and one in review). Microstructural development under conditions of controlled acceleration during directional solidification has been investigated; this has culminated in a Master's degree and will be submitted for publication. The above work not only contributes to our understanding of solidification phenomena but also defines the processing parameters for a successful microgravity experiment *while* providing a data base to which μg samples can be unequivocally compared and evaluated.

Final Report "The Influence of a Microgravity Environment on the Dendritic Morphology During Directional Solidification of Hypoeutectic Al-Si Alloys"

Eutectic and hypoeutectic aluminum-silicon alloys are the basis of the most important group of light metal casting alloys, yet much is still unknown about their solidification behavior. Directional solidification techniques afford the ability to investigate the alloys in a systematic manner, the results of which can be compared to theoretical predictions. Al-Si alloys are so considered in, "Columnar Dendrite Growth: Experiment and Theory," by W. Kurz and R.N. Grugel (Materials Science Forum, 1991, Vol.77, Trans Tech Publications, Switzerland, pp. 185-204).

It is well established that the mechanical properties of certain castings, e.g., turbine blades, are improved through directional solidification processing. This improvement is directly related to the microstructure, which typically consists of an aligned network of primary and secondary dendrites that is infilled with eutectic. Here the primary dendrites can be envisioned as continuous fibers extending the length of the casting (often increasing its strength and ductility); secondary arms can serve to isolate potentially detrimental phases. Furthermore, the material properties are also a function of the microstructural scale, which

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in turn depends on the solidification parameters of growth velocity (V), composition (C_o), and temperature gradient (G).

The compiled results of numerous experimental investigations have conclusively demonstrated the existence of unique relationships between the above parameters and the subsequent spacings between primary dendrites (λ_1), secondary dendrites (λ_2), and eutectic phases (λ_E), e.g. **Figure 1**. Theoretical analyses of the above have also been made, and while the fit between experiment and theory varies from system to system, qualitative agreement is seen.

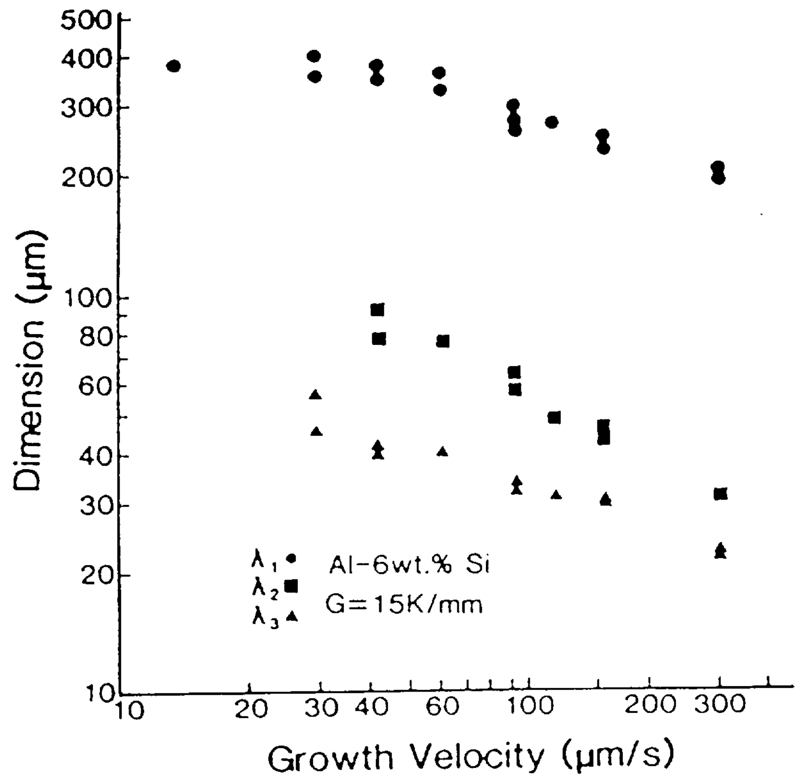

Figure 1: Primary (λ_1), secondary (λ_2), and tertiary (λ_3) dendrite arm spacing relationships as a function of the imposed growth velocity.

It is, therefore, relevant to understand the development of these microstructural constituents so that the material properties can be optimized and faithfully reproduced. This may be conveniently done by relating the spacing measurements (λ_1, λ_2, λ_E) to the solidification parameters (V, C_o, G).

Directional solidification studies of hypoeutectic alloys have recently been extended to investigate the relationship between primary dendrite trunk diameters and tertiary dendrite arm spacing, e.g. **Figures 2-4**. Complete reports are given in the following papers: "Evaluation of Primary Dendrite Trunk Diameters in Directionally Solidified Al-Si Alloys," by R.N. Grugel (Accepted for publication in *Materials Characterization*) and in "Secondary and Tertiary Dendrite Arm Spacings in Directionally Solidified Al-Si Alloys," by R.N. Grugel (Submitted for publication in *Journal of Materials Science*). Relevant conclusions from these studies include:

1. The primary dendrite trunk diameter has been shown to exhibit predictable behavior as a function of growth velocity, temperature gradient, and composition during constrained, directional solidification.

2. For the processing parameters of composition and temperature gradient, the as-plotted trunk diameters increased linearly with a slope of ~1/3 as a function of time in the solid-liquid "mushy" zone. This relationship might be expected in view of coarsening theory.

3. The demonstrated rapid response of the dendrite tip to changes in growth velocity and subsequent effect on the trunk diameter imply that the trunk diameter is a more representative measure of the local solidification conditions than primary dendrite, secondary dendrite, or eutectic spacings.

4. Secondary and tertiary dendrite arm spacings were both found to decrease as a function of increasing growth velocity for a given composition. The rate of decrease, $d\lambda_{2,3}/dV$, was found to serially increase as the Si concentration was decreased. The spacings also decreased as a function of increasing Si concentration for a constant imposed growth rate. The rate of decrease, $d\lambda_{2,3}/dC_o$, serially increased as the growth velocity decreased. The difference in rates is attributed to the existence of two fields in the mushy zone. Rapid coarsening of the branches occurs just behind the dendrite tips, and then rather abruptly transfers to a region where the spacing slowly increases; the relative contribution of each depends on the solidification parameters.

5. Coarsening of secondary arms was found, in general, to be proportional to time$^{1/2}$. For tertiary arms, time$^{1/3}$ behavior was found. The deviation of the secondary spacing from $t^{1/3}$ has been attributed to secondary dendrite arm migration up the imposed temperature gradient.

6. The difficulties expressed in measuring secondary dendrite arm spacings as compared to tertiary, suggest the latter, when present, to be better representatives of the solidification conditions.

The above work has been complimented by a recent study. Dynamical studies of dendrite trunk evolution have been made with the intent of evaluating them as an alternative means of establishing the solidification history during non-equilibrium freezing. This is reported on in detail in the Master's thesis (Major Advisor - R.N. Grugel) of Mr. R. Pratt which is expected to be completed this summer. A brief synopsis follows. **Figure 5** plots the primary dendrite arm spacing as measured from a sample which has been directionally solidified through a controlled acceleration of $3.96\mu\,ms^{-2}$. The curve labeled "Kurz and Grugel" denotes measurements made from steady-state growth experiments; that labeled "Hunt" is a theoretical prediction. Measurements of the primary dendrite arm spacing from the acceleration experiments are seen to vary little over the velocity range. In contrast, **Figure 6** shows that the trunk diameter measurements from the acceleration experiments follow very well the trend (curve labeled "Grugel") set by the steady-state measurements. Similar results are seen in **Figures 7 and 8** where the effect of a controlled deceleration ($-7.88\mu\,ms^{-2}$) was investigated. The data show that the trunk diameter responds to changes in growth velocity much more rapidly than primary dendrite arm spacings. These results give additional credence to the premise of utilizing the trunk diameter, in lieu of the primary dendrite arm spacing, as a microstructural characteristic which better reflects the actual solidification processing conditions, particularly under non-steady-state growth conditions.

Figure 2: Cross-sectional micrograph of an Al-6wt pct Si alloy with the trunk diameters noted. Growth Velocity=$300\mu ms^{-1}$, Temperature Gradient=$15Kmm^{-1}$.

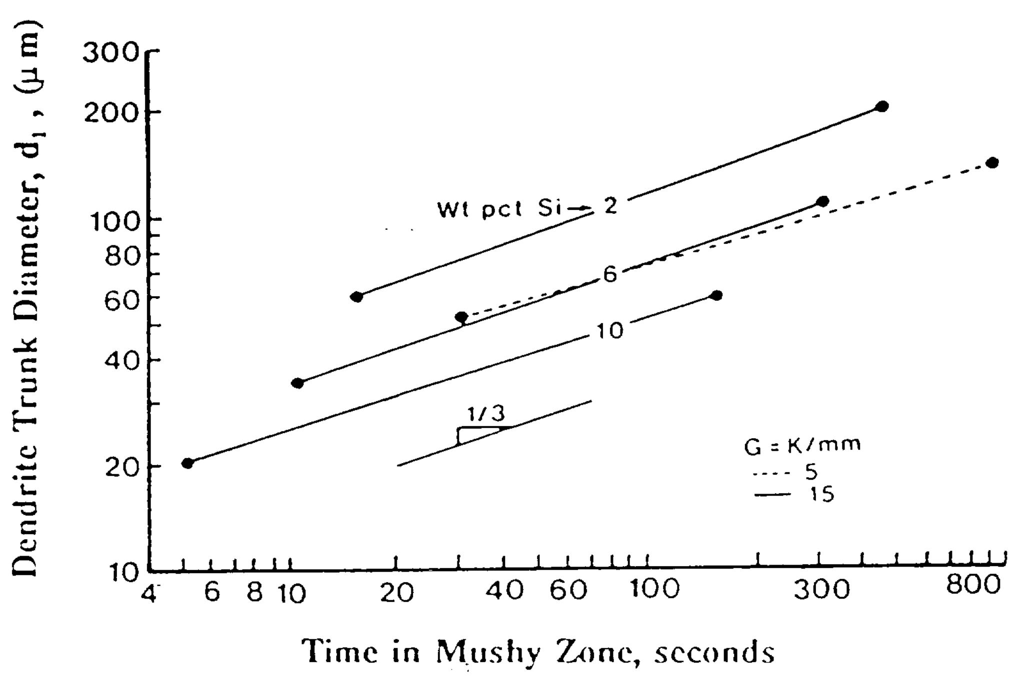

Figure 3: Primary dendrite trunk diameter as a function of time in the mushy zone. The end points on the left represent a growth velocity of 300μ ms^{-1}, the right ones 10μ ms^{-1}.

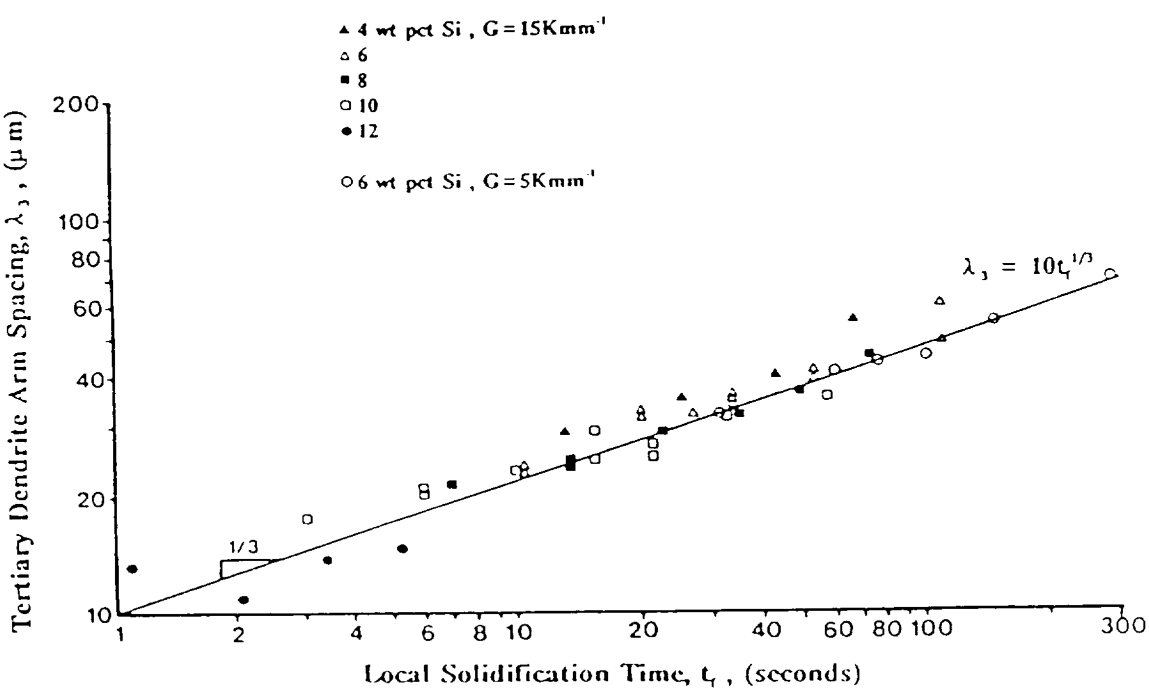

Figure 4: Plot of the measured tertiary dendrite arm spacings, λ_3, as a function of local solidification time, t_f.

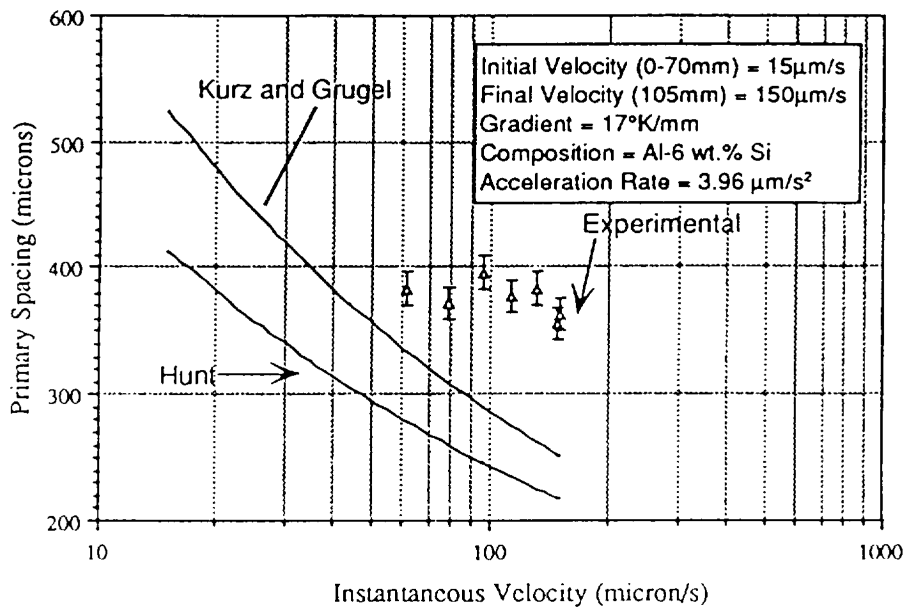

Figure 5: Measured primary dendrite spacing vs. acceleration for an Al- 6 wt pct Si alloy. Hunt's theoretical prediction is shown along with a curve based on the steady-state experiments of Kurz and Grugel.

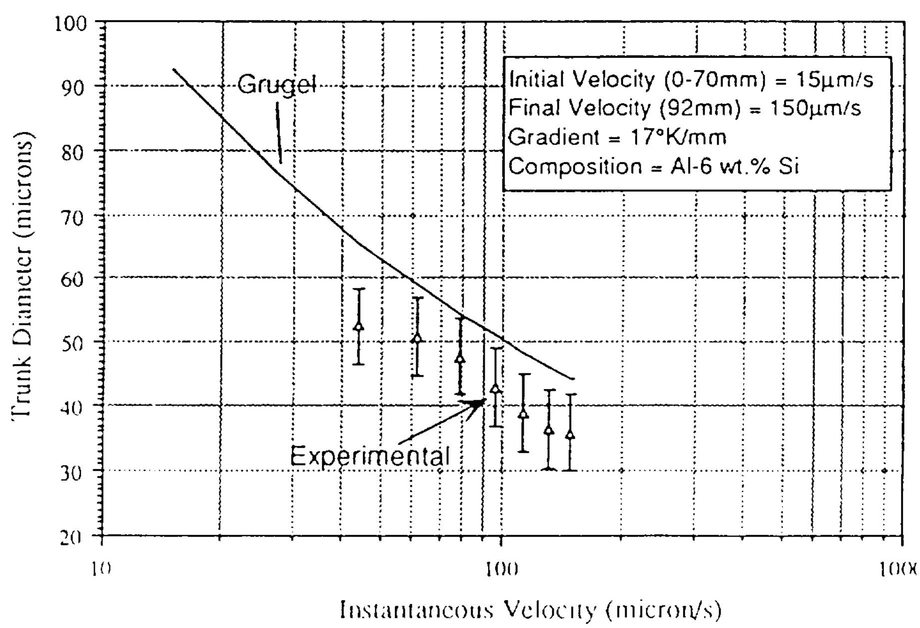

Figure 6: Measured primary dendrite trunk diameter vs. acceleration for an Al- 6 wt pct Si alloy. The experimental data are plotted in conjunction with a curve based on the steady-state measurements of Grugel.

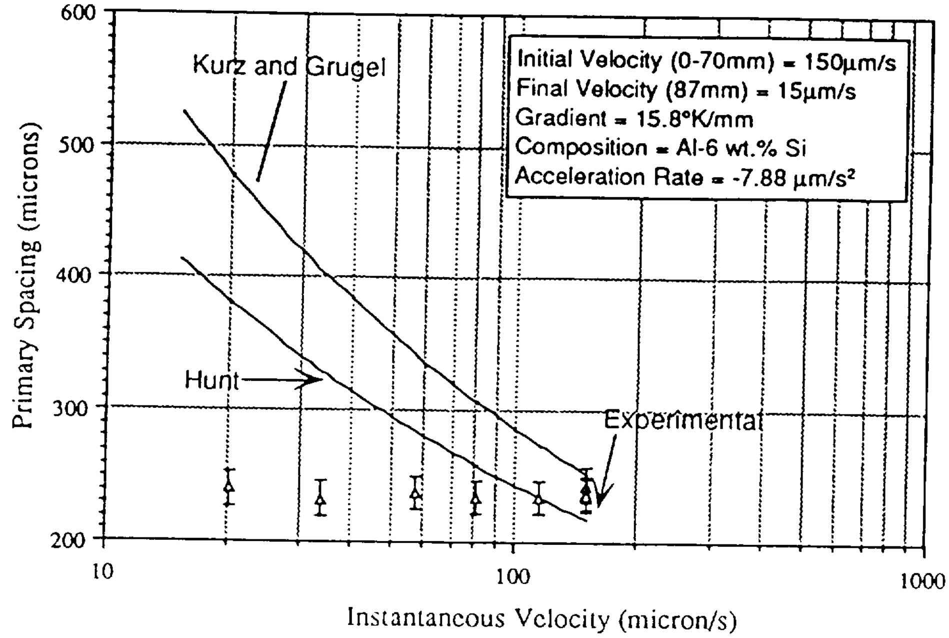

Figure 7: Measured primary dendrite spacing vs. deceleration for an Al- 6 wt pct Si alloy. Hunt's theoretical prediction is shown along with a curve based on the steady-state experiments of Kurz and Grugel.

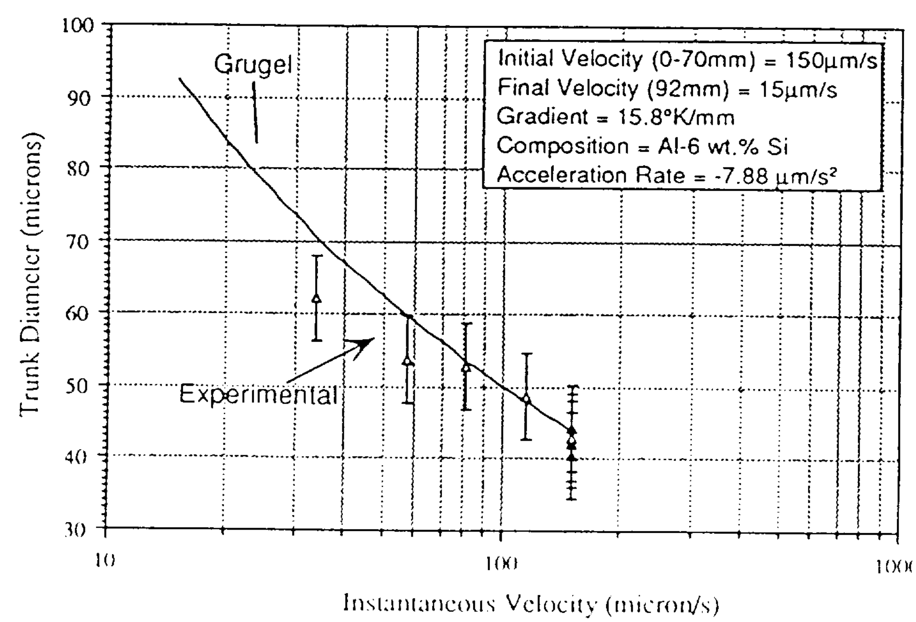

Figure 8: Measured primary dendrite trunk diameter vs. deceleration for an Al- 6 wt pct Si alloy. The experimental data are plotted in conjunction with a curve based on the steady-state measurements of Grugel.