Secondary Arm Coarsening and Microsegregation in Superalloy PWA-1480 Single Crystals: Effect of Low Gravity

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SECONDARY ARM COARSENING AND MICROSEGREGATION IN SUPERALLOY PWA-1480 SINGLE CRYSTALS: EFFECT OF LOW GRAVITY

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Abstract

Single crystal specimens of nickel base superalloy PWA-1480 have been directionally solidified on ground and during low gravity (20 sec) and high gravity (90 sec) parabolic maneuver of KC-135 aircraft. Thermal profiles were measured during solidification by two in-situ thermocouples positioned along the sample length. The samples were quenched during either high or low gravity cycles so as to freeze the structures of the mushy zone developing under different gravity levels. Microsegregation has been measured by examining the solutal profiles on several transverse cross sections across primary dendrites along their length in the quenched mushy zone. Effect of gravity level on secondary arm coarsening kinetics and microsegregation have been investigated. The results indicate that there is no appreciable difference in the microsegregation and coarsening behavior in the specimens grown under high or low gravity. This suggests that short duration changes in gravity levels (0.02 to 1.7 g) do not influence convection in the interdendritic region. Examination of the role of natural convection in the melt near the primary dendrite tips, on secondary arm spacings requires low gravity periods longer than presently available on KC-135. Secondary arm coarsening kinetics show a reasonable fit with the predictions from a simple analytical model proposed by Kirkwood for a binary alloy.

Introduction

An array of primary dendrites is produced during directional solidification of alloys in a positive thermal gradient, under growth conditions with large gradient of constitutional supercooling. It has been observed that the initial side-branch spacing near the tips of primary dendrites is about two to three times the dendrite tip radius (Refs. 1-3). The spacings between the neighboring side branches are observed to increase with the increasing distance from the dendrite tip. Several factors have been proposed in the literature, which may be responsible for the secondary arm coarsening. The coarsening may be due to the process of a simultaneous dissolution of smaller arms with sharper tip radii and growth of larger arms with less curvature (Refs. 4, 5). It may be due to the process of dendritic separation, i.e., the secondary arm dissolving and detaching from the primary dendrite (due to the sharp curvature which reduces the local liquidus temperature) (Ref. 5). The coalescence of the neighboring side-branches can also lead to coarsening (Refs. 6, 7). Measurements of the side-branch spacing from the tip of the primary dendrites to their base in the quenched mushy region of the microstructure have been used to obtain more insight into the side-branch coarsening mechanism (Refs. 2, 8). Kirkwood (Ref. 8) has recently proposed a simple analytical model to predict the side-branch coarsening kinetics in binary alloys. This model is especially suited to partial directional solidification and quenching experiments.

Several recent experiments have explored the effect of gravity on primary and secondary dendrite arm spacings. Reduced gravity has generally resulted in increased secondary arm spacings (Refs. 9-12). Directionally solidified polycrystalline MAR-M246 (Ref. 7) tended to exhibit an increased secondary arm spacing in portions of the sample solidified during the low gravity maneuver of the KC-135 parabolic flight, as compared to the portion which was solidified during the high gravity. In contrast, a recent microgravity experiment on an aluminum-copper alloy has shown decreased secondary arm coarsening kinetics (Ref. 13). Long duration low gravity experiments have, by now, well established that the reduced convection causes increased primary dendrite spacings (Refs. 14, 15). However, the exact mechanism by which this is brought about is not understood. It has recently been shown that the increased primary dendrite spacings observed in the low gravity grown aluminum-copper alloy sample can be explained by the primary arm spacing model due to Hunt (Ref. 15), by simply replacing the alloy growth speed, R, in the model with an order of magnitude estimate of the interdendritic fluid velocity (Ref. 15).

It is generally believed that the primary and secondary spacings are controlled by the solutal profiles in the

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melt, at the dendrite tip (G'L), and in the interden-
dritic region (G'p). Any change in G'c and G'p because
of the gravity driven convection will affect primary
dendrite spacings, their tip radii, initial side-branch
spacing and secondary arm coarsening kinetics. 

These solutal profiles also determine the elemental
microsegregation across primary dendrites produced
during directional solidification. Therefore in order
to understand the effect of reduced convection on the
primary and secondary arm spacings, it is important
to investigate its influence on the microsegregation.

The purpose of this study was to examine the effect
of reduced gravity on secondary arm spacings and on
the microsegregation of solutes in a multicomponent complex
commercial superalloy PWA-1480. The superalloy, PWA-1480
(nominal composition, Ni-12Ta-10.4Cr-5Co-5Al-4W-1.5Ti
(wt %), is used as a monocrystal turbine blade mate-
rial in advanced gas-turbine aerogines. This alloy
was selected for this study because a preliminary inves-
tigation has shown the band of increasing primary arm
spacings to correspond with the reduced gravity periods
of KC-135 parabolic flight (Ref. 17). Despite its mul-
ticomponent nature, this alloy has solidification behav-
ior which is very similar to a binary alloy. The final
solidification of PWA-1480 at the base of the primary
dendrite array occurs at nearly a constant temperature
(Ref. 18), similar to the isothermal eutectic solidifi-
cation in a binary system. Unlike the carbon contain-
ing superalloys, such as, MAR M-246, this alloy does
not have carbide precipitation (at a tempera-
ture between the liquidus and the eutectic tem-
peratures) to complicate the microsegregation analysis.

Since KC-135 flights are presently the only platform
available to obtain the low gravity growth, the effect
of gravity on the solidification behavior of this alloy
was explored by directional solidification experiments
during the "low" and high gravity periods of its maneu-
vers. The experiments were instrumented for in-situ
temperature measurements to ensure reproducible thermal
profiles. Single crystal specimens ([100] within a°
of growth direction) were used to reduce the measure-
ment uncertainties and scatter in the side-branch spac-
ing and microsegregation data.

Experimental

Details of the Bridgeman type directional solidifi-
cation apparatus are presented in Ref. 19. The hot
zone in the furnace assembly is about 10 cm long
and 1 cm in internal diameter. The water cooled copper
chill zone at the bottom end of the furnace is approxi-
mately 5 cm in length. Single crystal PWA-1480 cylin-
drical rods ([100] within a° of the growth direction)
were remelted in flowing argon atmosphere in alumina
crucibles (0.635 cm I.D. and 46 cm long), containing
two Pt-Pt 13 percent Rh thermocouples located along
the specimen length at a separation of about 0.5 cm.
The sample was so positioned in the furnace that
approximately 5 cm length of the original 7 cm long
bars was remelted. After a 20 min thermal soak the
sample was directionally solidified for about 3.5 cm at
growth rates in the range of 10-3 to 2.3x10-4 cm s-1.
When the top of the specimen was at a predetermined temper-
ature, usually near the liquidus temperature of the
alloy, 1610 K, the furnace was quickly withdrawn
and the sample was quenched by spraying water on the cruci-
bale surface. Typical cooling rates of approximately
50 K s-1 were recorded during quench by the thermocou-
ples located near the tips of primary dendrites. Exper-
iments were conducted on ground and on KC-135 aircraft
during its low gravity (20 sec duration, acceleration
w = 0.01 - 0.02 g) and high gravity (60 to 90 sec, accel-
eration = 1.7 g) periods of parabolic maneuvers.

Flight maneuvers and quench were synchronized to obtain
samples with the longest possible portion of their
mushy zone solidifying during either the low gravity or
the high gravity periods. Assuming that the growth
speed is identical to the specimen withdrawal speed,
the distances from the quenched primary dendrite tips
along the specimen length were correlated with the var-
ious high and low gravity periods of the flight.

The specimens were metallographically polished and
etched (etchant by volume: 33 acetic acid, 33 nitric
acid, 33 water and 1 hydrofluoric acid) to correlate
microstructural features, such as the tip and base of
primary dendrites, with the temperatures measured by the
two thermocouples. Primary dendrite spacings were mea-
sured on transverse sections (perpendicular to the growth
direction) to examine their variation along the specimen
length. Primary dendrite spacings reported in this
paper are equal to \( \lambda \), where \( \lambda \) is the specimen
cross-section area (transverse section) and \( N \) is the
number of primary dendrites on that cross-section.

Depending on the growth conditions, 200 to 600 primary
dendrites were observed and counted on the correspon-
ding specimen cross sections (18.58 to 20.14 mm²).
Secondary arm spacings were measured by averaging the
distance between five adjacent side branches on the
longitudinal section (parallel to the alloy growth
direction) of a primary dendrite as a function of dis-
tance from the dendrite tip. Each of the side-branch
spacing data reported here are the average of second-
ary arm spacings from four or five primary dendrites.

An Applied Research Laboratory Model SEM electron probe microanalyzer was used to examine
the microsegregation across the primary dendrites, in the
quenched interdendritic region. Because of the large
amount of microprobe data required for this study,
initially the ZAF (atomic number, absorption and flu-
orescence) corrected concentration values, obtained from
the microprobe measurements, were used to prepare a
calibration scheme. This calibration scheme was subse-
quently used for analyzing the raw microprobe data.

Results

Thermal Profile

Figure 1 shows a typical time dependence of the
accelerometer, furnace position, and sample tempera-
ture data for a sample which was directionally solidified at
a speed of 0.013 cm s-1 and quenched during the fifth
high gravity parabola. The thermal profiles from the
two thermocouples are also shown in this figure. The
thermal gradient (Gt) in the melt at the tip of the
primary dendrite array (assuming the tip temperature to
be the liquidus temperature, 1610 K) was obtained from
such temperature profiles.

Figure 2 shows a typical comparison of the thermal
profiles (temperature versus growth distance) in the
vicinity of the mushy zone, as recorded by the lower
thermocouples, during two different KC-135 experiments
at growth speeds of 0.013 cm s-1. The specimen IKC was
quenched with its dendrite tips in the low gravity
period. The other sample, 8KC, was quenched after one
mushy zone length (cell length) had solidified during
high gravity period of the flight. The thermal prof-
iles of the two specimens are nearly identical. The
Figure 1. PWA-1480 SUPERALLOY ACCELERATOR, FURNACE POSITION, AND SAMPLE TEMPERATURE DATA FOR A SAMPLE DIRECTIONALLY SOLIDIFIED AT 0.013 cm s\(^{-1}\) DURING SEVERAL LOW AND HIGH GRAVITY MANEUVERS AND QUENCHED DURING THE FIFTH HIGH GRAVITY PARABOLA.

Figure 2. THERMAL PROFILES NEAR THE LIQUIDUS TEMPERATURE FOR SAMPLES DIRECTIONALLY SOLIDIFIED AT 0.013 cm s\(^{-1}\) (13KC). Distance \(A\) marked in this figure indicates the cell length. The quenched primary dendrite tips are schematically shown on the right hand side. Start of directional solidification is on the left side. This figure shows that initially the primary dendrite spacings decrease along the length of the solidifying specimen before becoming almost constant. A steady-state solidification can therefore be assumed to occur after growth of about 1 cm of the specimen length. Nearly steady-state growth conditions are subsequently achieved for a length which is approximately equal to two to three times the cell length, before the sample is finally quenched.

Effect of Gravity

Side-Branch Coarsening Kinetics: Figure 5 shows the secondary arm spacing versus time (distance from the dendrite tip divided by growth speed) plots for specimens which were grown during KC-135 flights at 0.013 cm s\(^{-1}\) respectively. The high gravity (gh) and low gravity (gL) periods are also marked in these figures. The portions near the quenched end, showing the increasing secondary arm spacings from the tips of the primary dendrite, along the cell length, can be used to obtain the side-branch coarsening kinetics. The cell lengths observed in these specimens are schematically shown in these figures (lower right). For the growth rate, 0.013 cm s\(^{-1}\) (Fig. 5(a)), even the entire period of low gravity (approximately 20 sec) is not sufficient to obtain the growth of one complete length of the primary dendrite array (cell length = 0.48 cm). Due to the experimental difficulty of being able to achieve an exact synchronization among crucible withdrawal, flight maneuver and quenching, and the need to ensure the reproducible thermal profiles near the mushy zone, it was not possible to obtain specimens with one complete cell length forming during the low gravity period. On the other hand, the high gravity period (about 45 sec) is sufficient to obtain the side-branch coarsening along the entire length of the primary dendrite, Fig. 5(b).
FIGURE 3. - LONGITUDINAL MICROSTRUCTURES SHOWING THE ALIGNED PRIMARY DENDRITES IN THE QUENCHED MUSHY ZONE FOR SPECIMENS GROWN AT 0.013 CM S\(^{-1}\). THE TEMPERATURES AT THE TIP (1610 K) AND THE BASE (1550 K) ARE INDICATED. LOW-\(g\) AND HIGH-\(g\) REGIONS ARE MARKED FOR 13KC. FOR 17KC, WHOLE MUSHY ZONE HAS DEVELOPED UNDER HIGH-\(g\). TRANSVERSE SECTIONS ON WHICH MICROSEGREGATIONS WERE ANALYZED ARE INDICATED BY CUT-2 AND CUT-4.

FIGURE 4. - VARIATION OF PRIMARY DENDRITE SPACINGS ALONG THE LENGTH OF A SPECIMEN, SOLIDIFIED AT 0.013 CM S\(^{-1}\) (13KC). THE DISTANCE MARKED 'A' IS THE EXPERIMENTALLY OBSERVED CELL LENGTH. PRIMARY DENDRITES SHOW REASONABLY CONSTANT SPACINGS FOR A DISTANCE SLIGHTLY MORE THAN TWICE THE CELL LENGTH NEAR THE END WITH THE QUENCHED DENDRITE TIPS.
Figure 5. - Secondary arm spacing versus time plots for superalloy specimens directionally solidified at 0.013 cm s\(^{-1}\). Approximate average behavior is shown by the solid lines. The high gravity and low gravity periods are marked in these figures. The cell length in the mushy zone is also schematically shown.

Figure 5 shows that there is a large scatter in the data. The approximate average behavior is shown by the solid lines in these figures. The secondary arm spacings do not show an increase corresponding to the transition from high gravity to low gravity, as has been earlier reported in another directionally solidified superalloy, Mar M-246 (Ref. 9).

The initial data in Figs. 5(a) and (b) have been replotted for the two specimens grown at 0.013 cm s\(^{-1}\) in Fig. 6, as side-branch spacing versus coarsening time. Within the experimental scatter, the secondary arm coarsening kinetics appear to be the same for the high gravity and the low gravity periods. However, there is a large scatter in the data. The scatter in the side-branch spacing data was observed to decrease with the decreasing growth speeds.

Microsegregation: Figure 7 shows a typical transverse section (Fig. 7(a)) and the corresponding solute profiles (Fig. 7(b)), starting from the interdendritic eutectic region at one end and terminating at the interdendritic eutectic region at the opposite end. For tantalum, aluminum and titanium the solute contents increase from the core of the primary dendrite towards its periphery. This is the behavior expected for solutes with partition coefficients less than one. It is interesting to note that the nickel based binaries for these three solutes have partition coefficients less than one (Ref. 20). On the other hand cobalt and tungsten, with their partition coefficients based on nickel based binaries greater than one, show an opposite trend. Their solute contents decrease in going from the core of the dendrite cross section to its periphery. Chromium showed a reasonably uniform distribution across the primary dendrite and has not been studied in detail in this investigation. Solutal profiles such as these have been folded with respect to the center point "O" (Fig. 7(a)) and the distance information converted to fraction solid using the relation: Fraction solid, \( f_s = \frac{x}{d_o} \), where \( x \) is the distance along OA or OB and \( d_o \) is half the average distance (similar to AB in Fig. 7(a)) for the transverse section, just below the base of the primary dendrite array in the quenched mushy zone. Typically three to four dendrites were analyzed and the concentration data averaged over a \( f_s \) range of 1 percent.

Figure 6. - Comparison of the side-branch coarsening kinetics during directional solidification (growth speed 0.013 cm s\(^{-1}\)) of superalloy PWA-1480 in the low gravity and high gravity periods of the parabolic flight. Considering the scatter in the data, any influence of gravity on the secondary arm coarsening kinetics is not resolvable.
It is clear from Fig. 9 that the solute contents in the dendrite core (near zero fraction solid) are nearly the same for the transverse sections examined in the mushy zone. This indicates that the solid-state diffusion effects are negligible. In the presence of significant diffusion in the solid, the solute content at zero fraction solid will be expected to be higher on a transverse section closer to the base of the primary dendrite, as compared to that near the tip. For solutes having less than unity partition coefficients (Ta, Ti, and Al). Opposite would be the case for W and Co.

Discussion

Comparison of Side-Branch Coarsening Behavior with Theoretical Model: Kirkwood (Ref. 8) has recently presented a simple analytical model to predict the side-branch coarsening kinetics in binary alloys. This model is especially suited to partial directional solidification and quenching experiments. It assumes a constant temperature and composition of the interdendritic melt. It treats the coarsening process as simultaneous dissolution of smaller arms (spheres) with sharper tip radii and growth of larger arms with less curvature. The model predicts the following behavior,

$$d^3 = -(128/3)T/m_i C_0 (k - 1) H t$$  (1)

where, d is the side-branch spacing corresponding to the coarsening time t, $D_i$, the solute diffusivity in the melt, $\sigma$, the liquid-solid surface energy, $m_i$, the liquidus slope, $C_0$, the solute content of the alloy, k, the solute partition coefficient and $H/T$ is the entropy of fusion per unit volume. The experimentally observed coarsening behavior for superalloy PWA-1480 is compared below with prediction from the above relationship, treating the multicomponent superalloy as if it were a binary.

Figure 10 plots $\log_{10}(d)$ versus $\log_{10}(t)$ data obtained from several experiments. It contains the data from several specimens, grown at 0.001 to 0.023 cm s$^{-1}$, both on ground and on KC-135. The straight line drawn through the data is the linear least squared fit given as,

$$\log_{10}(d, \mu m) = (1.021 \pm 0.014) + (0.325 \pm 0.001) \times \log_{10}(t, \sec)$$

For this fit, the correlation coefficient is 0.825 and the relative standard deviation is 5.2 percent. The slope of this line, 0.325, is same as that expected from the above coarsening relationship, $D_i/k$. The experimentally obtained value, 1.2x10$^{-9}$ cm$^3$/s$^{-1}$, of the terms in the bracket in Eq. 1 obtained from the intercept on the Y-axis in Fig. 10, will now be used to obtain the expected $D_i/k$ value for PWA-1480 in the following manner. The terms within the bracket can also be expressed as
d$$D_i/k = (128/3)T/m_i C_0 (k - 1)/H$$

where $T_0 = m_i C_0 (k - 1)/k$ is the freezing range of the alloy (1610 K, liquidus and 1575 K, solidus). We will assume the $\sigma$ and $H$ value for PWA-1480 to be the same as for nickel, 255 erg cm$^{-2}$ (Ref. 21) and 2.77x10$^{-10}$ erg cm$^{-3}$ (Ref. 22) respectively. We will assume the coarsening temperature, T, to be the liquidus temperature, 1610 K. The $(D_i/k)$ value thus obtained by fitting the above equation to the experimental data, 1.2x10$^{-9}$ cm$^3$/s$^{-1}$, is in good agreement with the expected value.
mentioned coarsening relationship to the experimental data is about \(2 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\). The experimentally observed partition coefficients for the various solutes in superalloy PWA-1480 are in the range from 0.4 to 1.7 (Ref. 18). Thus the solute diffusivity in the PWA-1480 melt (D) would be predicted to be in the range from 0.8 to \(3.4 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\). This is in a reasonable agreement with reported solutal diffusivity, about 2 to \(8 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}\) (Ref. 23), obtained from the estimations based on the use of the constitutional supercooling criterion for plain front solidification of several superalloys.

Need for Long-time Low Gravity Experiments: It has recently been shown (Ref. 24) that the time required (\(t_r\)) to reach a certain fraction of final steady-state fluid velocity value (FR), after a change in gravity level, is approximately equal to \(-0.029 \ln(1-\text{FR}) \frac{r^2}{\mu}\), where \(r\) is the radius of the crucible and \(\mu\) is the kinematic viscosity. For a viscosity of \(6.1 \times 10^{-3} \text{ cm}^2 \text{ s}^{-1}\) (for nickel melt at its melting point, Ref. 25), and the crucible radius of 0.32 cm, about 2 sec will be required to reach the 99 percent fraction of the steady-state fluid velocities after any change in gravity. This suggests that during the parabolic maneuvers of the KC-135 flight, growth conditions were obtained where the convection in the melt was suppressed for about 18 sec. Similarly during the high-g portions of the flight, the increased convection in the melt was available for about 88 sec. Because of the very small dimensions of the interdendritic melt, much smaller than the primary arm spacings, 150 \(\mu\)m, the changed gravity effects will be felt by the interdendritic melt in times much shorter than 2 sec.

The final secondary arm spacings observed at the base of the primary dendrites in an array depend on the following factors:

1. The initial side branch spacing near the tips of primary dendrite array: This spacing is known to linearly scale with the tip radius (Refs. 1-3). The
tip radius is determined by the solutal profile in the melt at the dendrite tips. Convection in the melt is expected to influence this solutal profile in the melt at the dendrite tips. The solutal build up in the melt at the tips (for \( k < 1 \)) increases with decreasing growth speed. Influence of reduced convection on this solutal profile requires low-g and high-g experiments at growth speeds much slower than available on KC-135.

(2) The side-branch coarsening kinetics: This will be a function of convection in the interdendritic melt and the interdendritic solutal profiles. Comparison of specimen portions grown during low-g and high-g periods of the KC-135 parabolic flight, for their side-branch coarsening (Fig. 6) and interdendritic solute profile (microsegregation, Fig. 9) behavior, suggests that these are not influenced by the gravity levels examined in this study. However, for both of these, there is a large scatter in the experimental data.

(3) The coalescence of neighboring side-branches: The coalescence of neighboring side-branches is expected to be significant only in the interdendritic regions closer to the base of the primary dendrites. The coalescence process will be influenced by factors, such as, interdendritic precipitates, primary arm spacings, volume fraction of interdendritic melt, etc. As mentioned earlier, PWA-1480 does not have the complexity arising from the interdendritic precipitation. Since the interdendritic channels are very narrow near the base of the primary dendrites the coalescence process is not expected to be influenced by the changing gravity levels. This effect has not been investigated in this research.

The scatter in a plot, such as Fig. 9, depends on several factors, the microprobe measurement process (instrumental scatter), the scatter due to local microstructural inhomogeneities larger than the probe x-ray resolution (approximately 3 \( \mu \)m), problem of imperfect alignment of the primary dendrites with the growth direction, and the statistical variation in the primary dendrite arm size. The relative standard deviation of the concentration values, caused by the fluctuations
In the instrument settings and the statistical nature of the x-ray counting process, is about ±3 percent (Ref. 18). The scatter due to the local microstructural variations within the primary dendrite is minimal, as is evidenced by about 3 percent scatter in the composition data closer to zero fraction solid (Fig. 9). The major sources of scatter in the microsegregation, across the primary dendrites, are the variations in the primary arm size and its nonalignment with the growth direction. A perfect alignment will result in a fourfold symmetry in the transverse microstructure of the dendrites. This would result in a symmetrical solute distribution along the opposite sides of the dendrite core along "A" type paths (as shown in Fig. 7). Otherwise the solute content at a given distance from the dendrite core on one side would be different from that at the same distance on the opposite side, causing the scatter in the solute concentration versus fraction solid (fraction distance) plots. Contribution from this scatter would be zero at the dendrite core, and would increase with the increasing distance from the core. The scatter would be further enhanced when the data obtained from several primary dendrites with different alignments are superimposed. The fourth kind of scatter, due to the differences in the primary arm spacings, results from the errors in the fraction solid value calculated based on the average spacing near the eutectic isotherm, as has been done in this study. The variation in the primary dendrite spacing in the directionally solidified superalloy PWA-1480 specimens is about 10 percent.

During ground based experiments it has been observed that the scatter in the side-branch spacing data decreases considerably with the decreasing growth speed. The lower growth speeds will also make it possible to examine the side-branch coarsening kinetics over a much longer time period. However, the low gravity period of KC-135 parabolic flight is already too short. For solidifying even one complete length of dendrite array, at a growth speed of 0.013 cm s⁻¹, longer time, low-gravity partial directional solidification and quenching experiments, required for a better resolution of the influence of reduced gravity, are not possible on KC-135. Such experiments can be carried out in the low gravity environment provided by the space shuttle. Because of the absence of cycling gravity levels, such experiments at low gravity will produce a more regular dendrite array, than the specimens examined in this study. This will further reduce the scatter in the side-branch coarsening and microsegregation data.

Specimens grown at much slower growth speed (approximately 0.001 cm s⁻¹) than examined in this study, in the low gravity environment of space, can help us isolate the effect of reduced gravity on the convection in the interdendritic melt and in the melt ahead of the dendrite array.

Conclusions

Following conclusions can be drawn from this study on single crystal superalloy, PWA-1480, specimens directionally solidified on ground and during low gravity (20 s) and high gravity (60 to 90 s) periods obtained during parabolic maneuvers of KC-135 aircraft. These specimens were rapidly quenched after partial solidification to retain the mushy-zone microstructure and the solutal distributions.

1. The specimen length which can be solidified during low gravity time available from the KC-135 flights is much smaller than the mushy zone length of PWA-1480. Because of the insufficient low gravity time, no definite conclusions can be drawn about the effect of gravity on the secondary arm spacing.

2. Side-branch coarsening kinetics and the solutal profiles in the interdendritic melt are not significantly influenced by the gravity levels examined here, 0.01 to 1.7 g. This is considered reasonable because the array of closely spaced primary dendrites effectively dampens the convection in the interdendritic region. Experiments at growth speeds less than about 0.001 cm s⁻¹, to obtain about three to four times the cell length directionally solidified in low gravity, are required to draw definite conclusions about the effect of reduced convection in the melt ahead of primary dendrite tips, on the secondary arm spacings. These experiments are feasible only in the long duration microgravity environment of space.

3. Measurement of the side-branch spacing along the length of the primary dendrites, from their quenched tip to their base, shows that the secondary arm coarsening kinetics in PWA-1480 are in a reasonable agreement with the behavior expected from the simple analytical model of Kirkwood (Ref. 8), developed for binary alloys.

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References


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**Supplementary Notes**
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**Abstract**

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