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SOLIDIFICATION RATE INFLUENCE ON ORIENTATION AND MECHANICAL PROPERTIES OF MAR-M-246+Hf

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16. ABSTRACT

The influence of solidification rates on the orientation and mechanical properties of MAR-M-246+Hf was studied. The preferred orientation was found to be (001) for single crystals, with all samples with 45° of (001).

Tensile tests were performed at room temperature. The anisotropy of directionally solidified MAR-M-246+Hf was demonstrated by gage section deformation.

Dendrite arm spacing and crystal growth were found to depend on solidification rates and source material conditions. The greatest strength occurred at lower solidification rates. Some single crystals were grown by control of growth rates without seeding.

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INTRODUCTION

The need for high temperature gas turbines has resulted in the development of superalloys for use as turbine blades. Greater engine efficiency and power are possible by raising the turbine operating temperature. However, improved life expectancy of the blades requires either cooling the blades or operation at temperatures which affect the material properties. Conventional methods call for the extraction of compressed air at different stages, resulting in a loss of power and efficiency. Superalloys, with their increased mechanical properties, allow gas turbines to operate at higher temperatures without the losses from extracting cooling air [1]. How these increased mechanical properties are achieved is the subject of current investigation.

The control of directionally solidified (DS) and single crystal (SC) nickel base superalloys such as MAR-M-246+Hf allows the determination of the influence of crystallographic orientation on mechanical properties. DS alloys are highly anisotropic and failure is usually by fracture along grain boundaries. Hafnium is added to strengthen the grain boundaries and stop cracking during solidification. SC alloys do not need Hf since secondary grains are avoided by casting at lower solidification rates.

The purpose of this preliminary work was to gain a basic understanding of the anisotropy of DS and SC MAR-M-246+Hf. The intent was to directionally solidify samples for three reasons: (1) to determine the preferred growth orientation, (2) to learn how grains grow out and what influences their growth, and (3) to determine the effects of orientation on mechanical properties.

APPARATUS

MAR-M-246+Hf was directionally solidified (DS) in the platinum wound resistance furnace shown in Figure 1. The furnace core (platinum wire wound on an alumina tube) was surrounded by insulation, placed on a copper quench block, and encased in a can. Furnace temperatures were controlled by a Pt-Rh thermocouple alongside the core.

The high purity alumina crucible had three major sections: (1) upper stage loading and drop pin, (2) solidification zone, and (3) alumina crucible and stand. Samples of MAR-M-246+Hf were placed on the drop pin and purged with argon at 2.5 psig. A constant argon purge was necessary to prevent oxidation of the MAR-M-246+Hf due to contamination by the atmosphere, and to reduce the evaporation rate. The argon flowed past the unmelted sample and out a vent in the alumina mount. Without a vent, gases could be trapped during solidification and expand, thus cracking the crucible.

The temperature of the furnace was raised in steps to 1512°C to avoid cracking the crucible, and the samples were dropped onto the alumina mount. In the solidification zone there was an average temperature gradient of 75°C/cm along the sample length.

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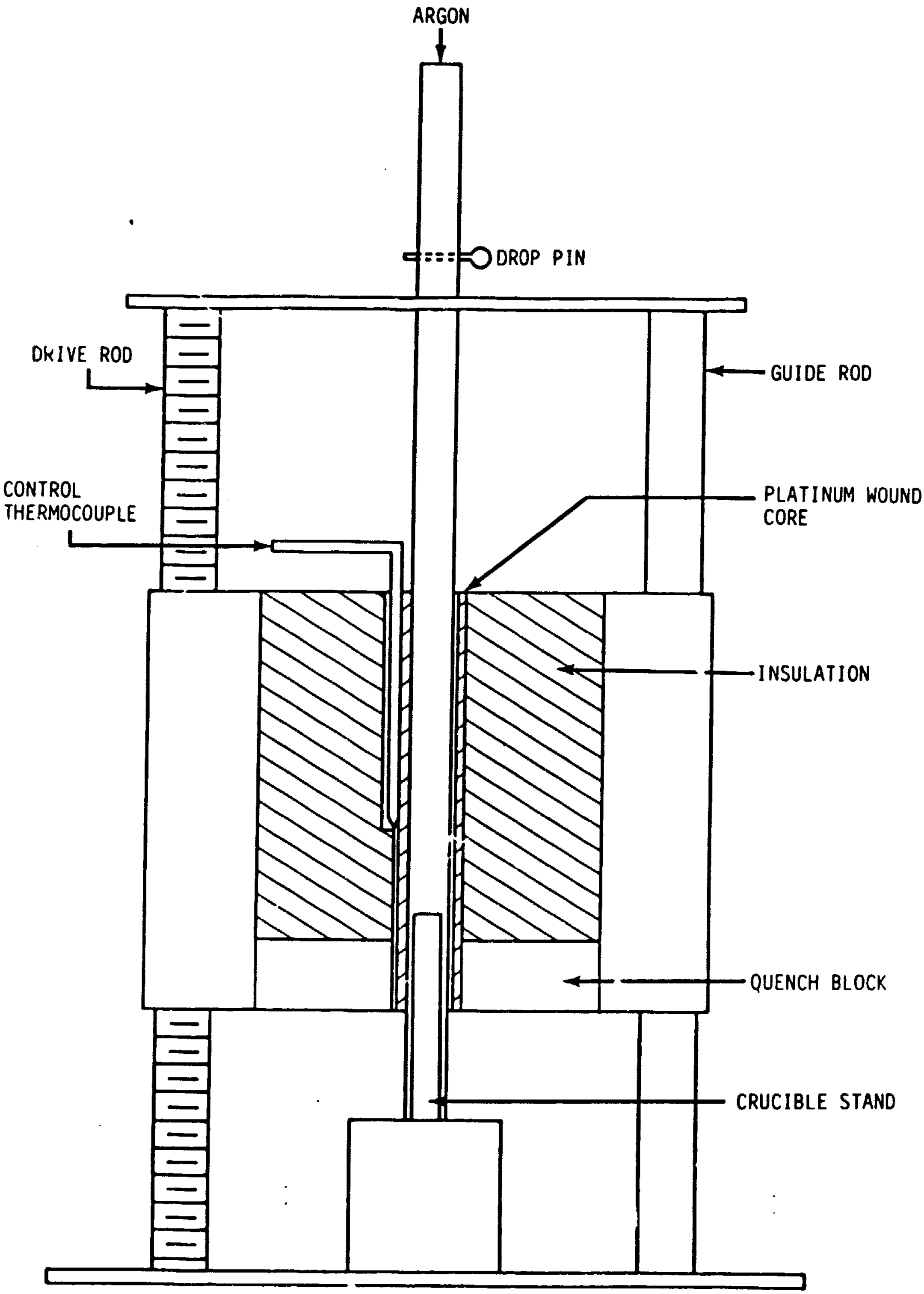

Figure 1. Directional solidification furnace.

The solidification zone temperature was allowed to reach equilibrium and solidification begun by moving the furnace assembly along the crucible. DS MAR-M-246+Hf was slowly cooled in the furnace to room temperature and removed from the alumina crucible. The samples had both ends polished, etched, and photographed, with some samples mounted for transverse examination. Back reflection LAUE photographs were taken at various orientations: (1) with the X-ray beam normal to the ends, (2) rotated, and (3) with the beam parallel to the ends. For multigrain samples, selected grains were similarly analyzed. The orientation of each grain was plotted on a stereographic projection and recorded. Specimens were tested in a tensile test machine at room temperature. Load versus strain was recorded, giving 0.2 percent yield strength, ultimate strength, and modulus of elasticity.

RESULTS

Twenty-two (22) MAR-M-246+Hf samples were directionally solidified in lengths to 5 cm at growth rates from 3.28 to 13.21 cm/hr. Each sample was polished and photographed to determine growth patterns and dendrite arm spacings. Back reflection LAUE X-ray photographs were taken to determine growth orientations. The preferred orientation of single crystal DS samples was (001). The range of deviation from (001) was 45 deg for all samples.

Figure 2 shows the primary dendrites formed in regular arrays. The primary dendrite arm spacings were found to decrease with increasing solidification rates (Fig. 3, Table 1).

Results of mechanical properties tests are given in Table 1 and a representative sample after testing is shown in Figure 4. Catastrophic failure occurred at 13 times the 0.2 percent yield strain for polycrystals and 21 times the 0.2 percent strain for single crystals.

DISCUSSION

Table 1 gives representative data for three solidification rates. The primary arm spacing is shown to increase as the growth rate decreases. Work is continuing to obtain an accurate profile of strength change with growth rate for DS versus SC samples.

The anisotropy of DS MAR-M-246+Hf is demonstrated by the change in shape of samples after tensile tests (Fig. 5). The samples distorted before fracture, resulting in an oval shape. Attempts to obtain LAUE X-ray photographs of failed specimens were unsuccessful due to the extreme deformation. SC tensile specimens did not distort as much as the DS samples. In Figure 4, a failed tensile specimen is shown with one section to reveal the progression of slip lines (not Lüders lines) along the section. Lüders lines are caused by areas of stress concentration, and form bands due to constant stress [4]. Slip lines are elliptical steps revealing deformation on parallel planes.

The usual stress-strain curve for a polycrystalline metal shows a region just after yielding begins where strain hardening occurs. Further yielding requires more stress due to the interference to further slip from grain boundaries and adjacent crystals [2]. This strengthening is found in most engineering metals, however, the stress-strain curves obtained during tensile tests for SC and polycrystal MAR-M-246+Hf showed no distinct strain hardening region. The lack of this strain hardening region on the stress-strain curve demonstrates the constant stress concentration which causes formation of Lüders lines.

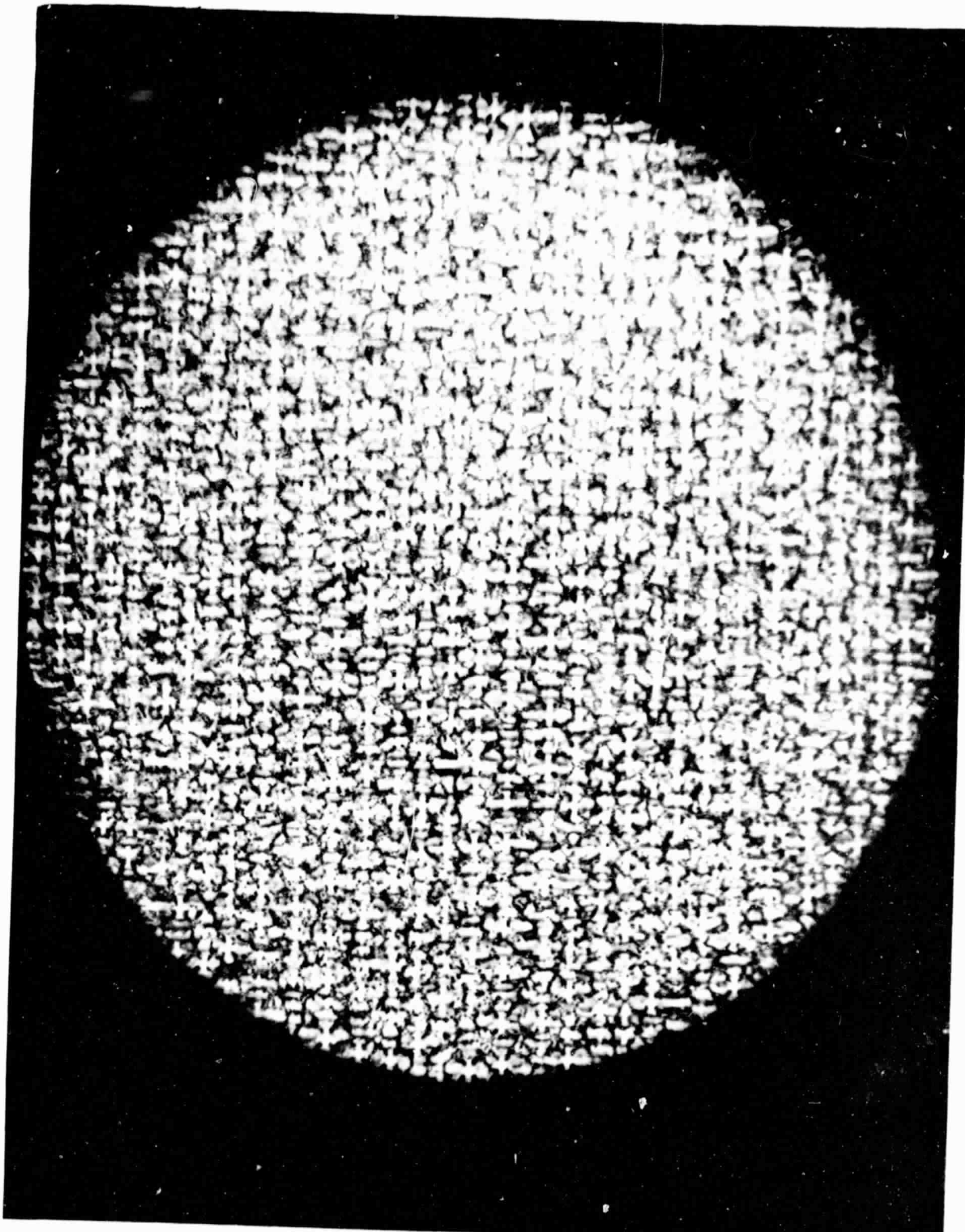

Figure 2. Dendrite spacing in single crystal MAR-M-246+Hf.

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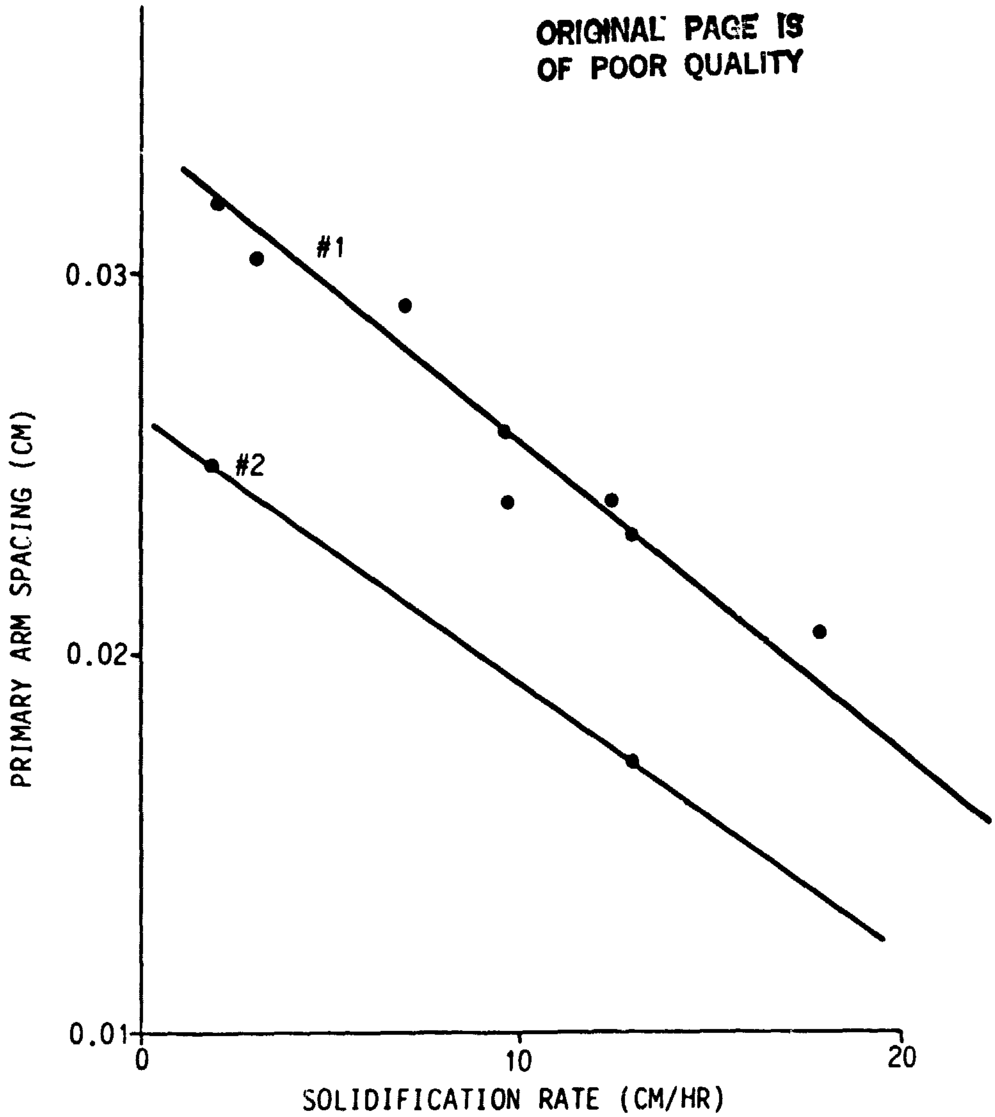

Figure 3. Primary arm spacing trend.

TABLE 1. SAMPLE DATA

Sample *	Growth Rate (cm/hr)	Primary Spacing (cm @ 50X)	Elastic Modulus (GPa)	Yield Strength (MPa)	Ultimate Strength (MPa)
DS	12.36	0.0237	167	743	863
SC	6.48	0.0272	294	853	920
SC	3.28	0.0291	205	703	786

*DS – Directionally Solidified
SC – Single Crystal.

Figure 4. Failed tensile specimen showing slip lines

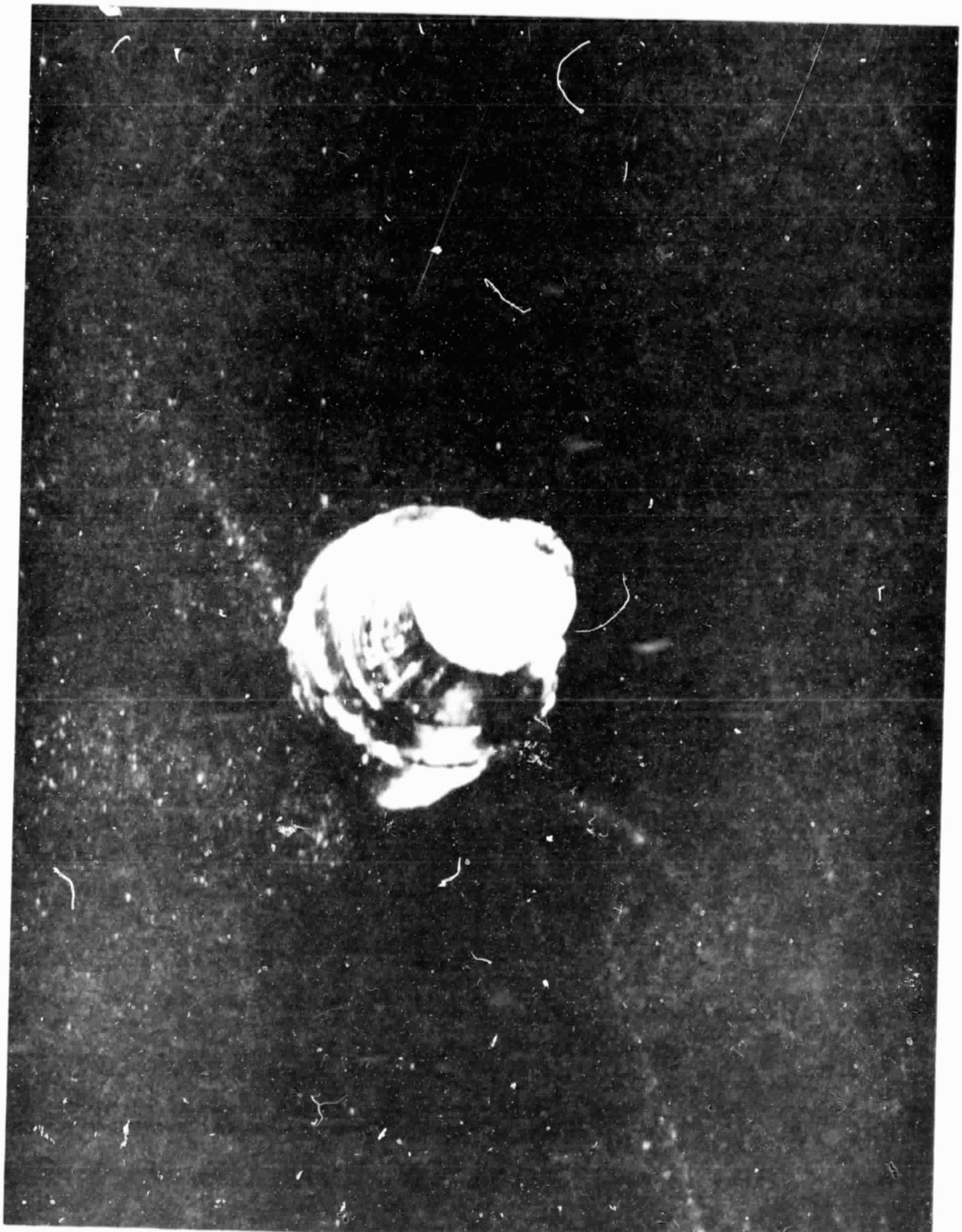

Figure 5. Transverse view of failed tensile specimen.

The least squared line fit for data points in Figure 3 is represented by:

$$d = 0.02625 - 0.00072\ (R) \qquad (1)$$

$$d = 0.03350 - 0.00081\ (R) \qquad (2)$$

where d is the arm spacing and R is the solidification rate.

It has been shown that for DS superalloys, the relationship controlling dendrite arm spacings follows the relation $\log d = -4.705 - 0.2393 \log R$, and also the general equation $d \propto (R)^{-0.24}$. This also agrees with the relationship predicted by Hunt, $d = AR^{-0.25}\,G^{-0.5}$ [5]. A log-log plot (Fig. 6) of the data from Figure 3 resulted in two equations:

$$\log d = -4.688 - 0.2381 \log R \qquad (1)$$

$$\log d = -4.592 - 0.1868 \log R \qquad (2)$$

These equations agree with those of previous work on dendrite spacing in DS superalloys.

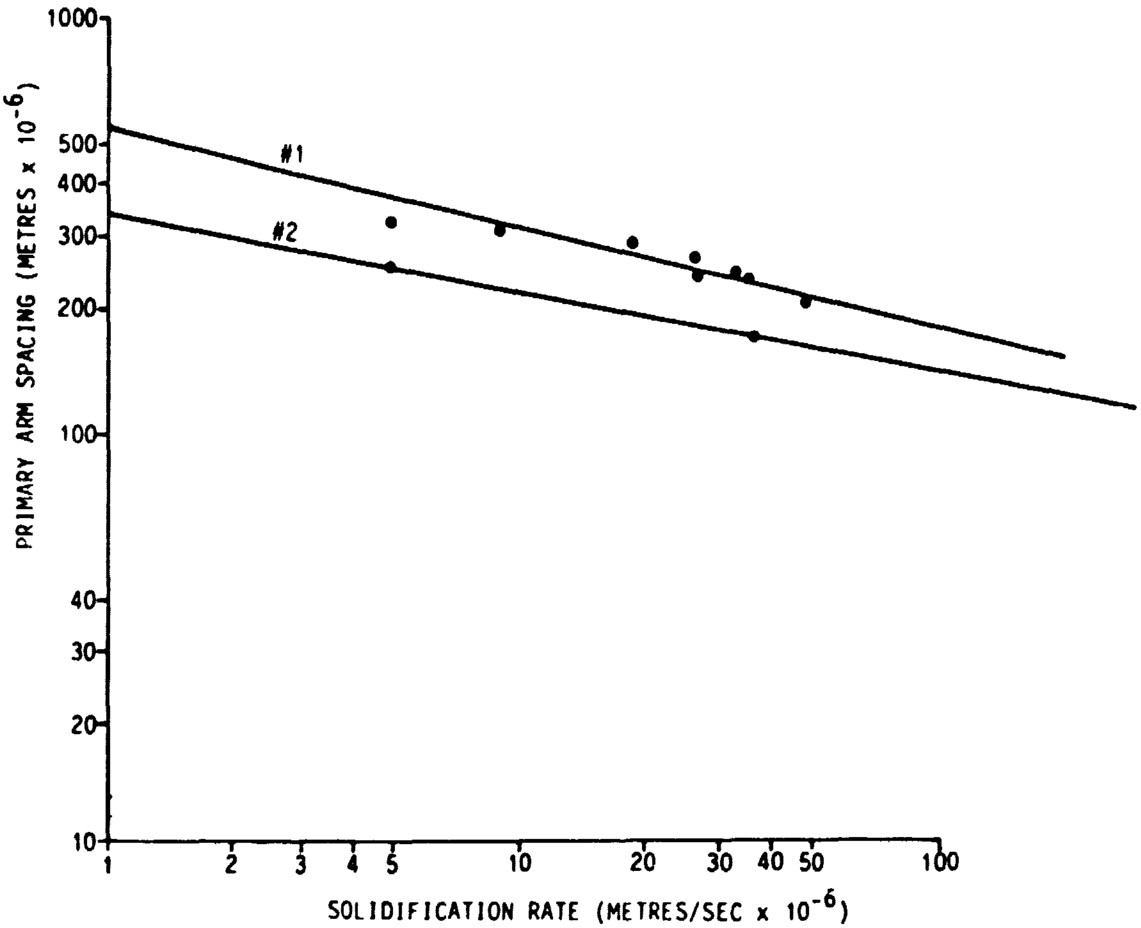

Figure 6. Primary arm spacing dependence.

Dendrite arm spacing is a good indication of how solidification affects structure and mechanical properties. Crystal growth (i.e., dendrite arm spacing) is controlled by thermal gradients where new crystals nucleate as a result of extracting latent heat without supercooling the melt [3]. These thermal gradients are affected by the following factors:

1) Mechanical stresses in the base material

2) Thermal stresses due to withdrawal and cooling rates

3) Non-homogeneous solute

4) Contamination by external substances

5) Inclusions found in metals.

This work attempted to gain insight into how factors within the metal influenced crystal growth and thus, mechanical properties. Mechanical and thermal stresses were controlled by consistent preparation and withdrawal of all samples. Contamination was reduced by use of high purity alumina crucibles. Inclusions within the material and the alloy homogeneity were determined by the source material.

The major factors influencing mechanical properties in DS and SC MAR-M-246+Hf were found to be the preferred orientation (001) and the solidification rates, with the greatest strength occurring at slower rates. The slower rates allowed the dendrites to form in uniform patterns, and facilitated crystal growth near the (001) with some samples forming single crystals.

It should be possible to obtain specific mechanical properties by control of the factors that influence crystal growth. To obtain a complete picture of how each of the solidification factors affects the mechanical properties of superalloys, further testing is required, including seeding to produce single crystal samples.

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