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1996

NASA/ASEE SUMMER FACULTY FELLOWSHIP PROGRAM

MARSHALL SPACEFLIGHT CENTER
THE UNIVERSITY OF ALABAMA

SOLIDIFICATION INTERFACE SHAPE AND LOCATION DURING PROCESSING IN HIGH GRADIENT FURNACE WITH QUENCH

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INTRODUCTION

High Gradient Furnace with Quench (HGFQ) is being developed to facilitate metals processing experiments aboard the International Space Station. The general furnace schematic is depicted in Fig. 1. The sample is centered in an annular furnace and is held fixed during processing. The furnace itself is made to translate over the sample. Once in process, heat will flow through the sample from the Heater Zone to the Chill Zone. If operating conditions are correct, the solidification interface will stand in the gradient zone. Objectives of the HGFQ process are to provide a high gradient for the solidification with the solidification interface properly positioned in the gradient zone.

At the recent RDR for HGFQ, one of the panelists raised the question about the suitability of HGFQ for potential future PIs. Specifically, it was stated by the design team at RDR that the present HGFQ design would provide a radius of curvature of the solidification interface of at least one sample diameter. The RDR panel argued that this was too small, and that most investigators would need a radius of curvature larger than this.

The requirements established by the current PIs are shown in Table 1. Note that these requirements do not contain any specification about the interface shape. However, these requirements do define the envelope of operational parameters for HGFQ.

The objectives of the present investigation are to 1) determine a suitable means of quantifying the interface shape, and 2) investigate the interface shape and how it is affected by processing parameters. The processing parameters to be considered are 1) sample material, 2) sample diameter, and 3) gradient zone length.

COMPUTATIONAL METHODS

The computer package FIDAP was used to investigate the process. FIDAP is a general purpose finite element analysis program which is especially applicable to heat transfer problems involving fluid flow. The current investigation does not make use of FIDAP's fluid flow analysis methodology, but in future the convection in the sample during ground-based testing could be simulated by adding this feature to the present model.

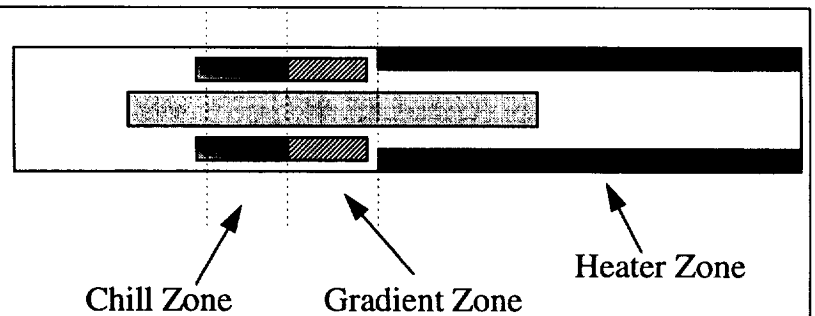


Figure 1. Furnace Schematic

TABLE 1. PI Requirements for HGFQ

PI	Material	Diameter	Hot Temp.	Gradient	$V_{translation}$
Stefanescu[1]	Aluminum?	6-10mm 10 mm	700-800 C < 900 C	80-100 C/cm 70-100 C/cm	0.1- 50 μm/s 0.5-150 μm/s
Andrews[2]	Al-Indium	10 mm	1000-1100C	80-100 C/cm	1.0-10 μm/s
Poirier[3]	Pb-23%Sn	6-10 mm	unspecified	50 C/cm	2-200 μm/s
Poirier[4]	Al-15%Cu	6-10 mm	unspecified	140 C/cm	12-200 μm/s
Trivedi[5]	Al-4%Cu	6-10 mm	unspecified	40-140 C/cm	1-48 μm/s
Trivedi[5]	Al-15%Cu	6-10 mm	unspecified	140 C/cm	1-48 μm/s

[1] From RDR - values listed appeared in different talk segments

[2] From RDR

[3] Letter/fax from David Poirier to Dorothy Hubbard dated June 21, 1996

[4] Letter/fax from David Poirier to Dorothy Hubbard dated June 27, 1996

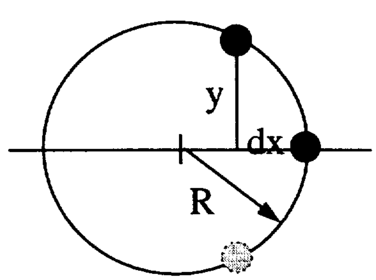
[5] Letter/fax from Rohit Trivedi to Dorothy Hubbard dated July 3, 1996

The computational approach employed is to fix the sample at a location and compute the steady-state temperature distribution in the sample and the furnace. After the temperature field is obtained, the solidification interface is identified by the temperature contour corresponding to the phase change temperature.

The steady-state mode is believed to closely approximate the temperature field during "slow" processing of the sample. Obviously, at higher translation velocities the nonstationary effects will become important.

RADIUS OF FLATNESS

A suitable measure of the shape is needed in order to compare results from different cases. The most intuitive might seem to be the radius of curvature, obtained by passing the equation of a circle through 3 consecutive points. However, this measure of curvature can result in unrealistic implications of flatness, particularly where an isotherm curves at the wall. A better idea is the radius of flatness (RoF) which is defined to be the radius of a circle passing through the point on the centerline, any point off the centerline, and its mirror image on the other side of the centerline. Calculation of the radius of flatness is accomplished via:



$$R = (y^2 + dx^2)/2dx$$

Calculation of the RoF will result in a distribution of flatness across the thickness. This distribution is depicted in Table 2. for a typical case. The RMS average of these is computed and used to quantify the shape of the interface.

TABLE 2. Radius of Curvature and Radius of Flatness

R	local RoC	diams	local RoF	diams	global RoF	diams
0.0000e+00	3.64e-02	3.7	3.64e-02	3.7	3.64e-02	3.7
6.1940e-04	5.27e-02	5.3	1.53e-02	1.5	4.30e-02	4.3
1.2388e-03	8.99e-02	9.1	1.14e-02	1.2	4.98e-02	5.0
1.8581e-03	2.94e+00	297.1	1.15e-02	1.2	5.98e-02	6.0
2.4775e-03	2.51e-01	25.3	1.27e-02	1.3	7.21e-02	7.3
3.0969e-03	1.38e-02	1.4	4.48e-03	0.5	6.31e-02	6.4
3.7162e-03	5.23e-03	0.5	1.68e-03	0.2	4.13e-02	4.2
4.3356e-03	1.20e-02	1.2	1.33e-03	0.1	3.24e-02	3.3
RMS->	1.05e+00	105.5	1.58e-02	1.6	5.14e-02	5.2
Avg->	4.2569e-01	43.0	1.1839e-02	1.2	4.9746e-02	5.0

RESULTS

The baseline configuration for calculation is as follows:

Steady-State Analysis
25% Processed Sample
Crucible (no gap or cartridge)
Argon atmosphere
PAN coupling to chill block
900 W/m^2-C cooling on back of chill block
1373 K Hot Zone Setpoint
(1123 K for Stefanescu and Pb 23%Sn)

The results for the baseline calculation are seen in Table 3. The smallest curvature results for the case of Stefanescu, and that is because the solidification occurs outside the gradient zone. For any of the alloy systems, the radius of flatness is much larger.

Table 4 shows the results of varying the sample diameter for the Al 4.5%Cu system. Note that shrinking the diameter increases the axial gradient, but has an adverse effect on the interface curvature.

Table 5 shows the effect of an increased gradient zone length on the Al 4.5%Cu alloy. For the 1100 C setpoint, the gradient is reduced, and the RoF is in fact increased slightly. For the 850 C setpoint, the RoF is increased slightly, and the gradient is increased slightly as well.

CONCLUSIONS

Radius of Flatness values for the liquidus isotherm of different aluminum alloys processed in HGFQ range from 3.1 to 11.1 sample diameters under baseline conditions. Decreasing sample diameter does not appear to be a means of increasing RoF. Increasing the gradient zone length appears to provide a means for increasing RoF.

TABLE 3. Results for Baseline Case

Material	PIs	Location (cm)	Gradient C/cm	RoF Liq	RoF Sol
Al	An	10.1	122	3.4	--
Al	St[1]	15.1	33	3.1	--
Al 4.5%Cu	Po/Tr	9.71	100	11.1	64.3
Al 15%Cu	Po/Tr	9.49	110	6.1	1086
Pb 23%Sn	Po[1]	8.34	120	305	5.3*

1 - Setpoint 1123 K

* -approximate result since mesh was > 300 μm

Note: Gradient zone is from 7.985 cm to 10.985 cm

TABLE 4. Results for Smaller Diameter - Al 4.5%Cu

Diameter	Hot Zone (C)	Chill Block (C)	Location (Liq) (cm)	Gradient C/cm	RoF Liq (diams)	RoF Sol (diams)
10 mm	1100	68	9.71	100	11.1	(-)64.3
10 mm	850	55	13.5	33	4.5*	11.9*
6mm	1100	65	9.94	102	6.8	405
6mm	850	52	13.4	36	4.1*	11.1*

* -approximate result since mesh was > 300 μm

Note: Gradient zone is from 7.985 cm to 10.985 cm

TABLE 5. Effect of Extended Gradient Zone

Length	Hot Zone (C)	Chill Block (C)	Location (Liq) (cm)	Gradient C/cm	RoF Liq (diams)	RoF Sol (diams)
3 cm	1100	68	9.71	100	11.1	(-)64.3
3 cm	850	55	13.5	33	4.5*	11.9*
5 cm	1100	n/a	10.8	88	12.1*	517*
5 cm	850	65	14.2	42	5.5*	28.8

* -approximate result since mesh was > 300 μm

Note: Gradient zone starts at 7.985 cm