EFFECTS OF THERMAL VARIABLES ON THE GROWTH OF SINGLE CRYSTALS OF

NI-BASE SUPERALLOYS

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Summary

The columnar and single crystal castings are most commonly manufactured by the Bridgman method, in which the control of heat transfer phenomena is most critical. For the understanding of the heat transfer, we developed a computer program for two dimensional transient heat flow analysis and compared the results with the experimental values.

Introduction

Columnar and single crystal castings of Ni-base superalloy have begun to be used for gas turbine airfoils of jet engines. As columnar and single crystals have excellent heat-resisting properties (especially high-temperature strength), use of these castings makes it possible to heighten the inlet gas temperature and remarkably increase total plant efficiency. Accordingly in a few years they will also be applied to heavy-duty gas turbines, but in this case there are various problems to be solved, such as enlargement of the size of single crystal castings or improvement of solidification process and efficiency. Most of the columnar and single crystal castings are manufactured by the withdrawal unidirectional solidification method. In this method the control of heat transfer phenomena is most important. If we grasp these heat transfer phenomena quantitatively, we can manufacture single crystals of high qualities speedily and productively by the proper control of them.

Concerning the heat transfer phenomena in the Bridgman method, or unidirectional solidification method, analyses have been made by Giamei (1), Naumann (2), El-Mahallawy (3) and Clyne (4)(5). But all of these are calculations under specific conditions, therefore, for our experiment on the growth of single crystals it was necessary to examine anew the effects of the fundamental factors by calculation. For this purpose we developed a computer program for two dimensional heat flow analysis and compared the results with the experimental values.

Method of Calculation

The calculation of temperature change during solidification of the castings was performed by an explicit finite difference scheme under the following assumptions.

Assumptions

- 1) The thermal properties of the castings and the mold (density, specific heat and thermal conductivity) are fixed independent of temperature.
- 2) The temperature of the atmosphere is fixed in the susceptor and outside the susceptor, respectively.
- 3) The heat flow between the mold and the atmosphere, and between the castings and the atmosphere is dealt with as a Newton type heat transmission and apparent heat transfer coefficients are used.
- 4) Apparent heat transfer coefficients are fixed inside and outside the susceptor, respectively.
- 5) Heat resistance between the castings and the mold is zero (infinite heat transfer coefficient).

Calculation

In calculation for the purpose of modeling the withdrawal of the mold, we changed apparent heat transfer coefficient and atmospheric temperature as a function of time and distance from the chillplate.

In Fig. 1 the height of the model (b) is 25 cm, the diameter of the castings is 2 cm and the thickness of the mold is 0.5 cm; the size is almost the same as that of the mold in the experiment (a). The number of element meshing is 7X21 and the selector part with a complicated shape is simplified into a 1 cm diameter column.

Table 1 lists the physical properties used in the calculation. The density, specific heat and thermal conductivity were selected from prior works.

(a) Mold (b) Calculation model

Fig.1 Mold and calculation model

The apparent heat transfer coefficient on the surface of the mold was determined from measurement.

Table I. Physical Properties Used in the Calculation

		standard	variation
Density(metal)	(g/cm ³)	7.6	
Specific heat (metal)	(cal/g.deg)	0.11	
Thermal conductivity(metal)	(cal/cm.°C.s)	0.1	
Liquidus	(°C)	1290	
Solidus	(°C)	1250	
Latent heat of solidification	(cal/g)	70	
Density (mold)	(g/cm ³)	1.8	
Specific heat (mold)	(cal/g.deg)	0.25	
Thermal conductivity (mold)	(cal/cm.°C.s)	0.002	
Time increment	(s)	1.0	
Heat transfer coefficient (cal/cm ² .s.deg)	casting-chill	0.01	0.1~0.0001
	mold-chill	0.005	
	mold-susceptor	0.0015	
	mold-atmosphere	0.0007	
Susceptor temperature	Ts (°C)	1550	1350~2000
Chill plate temperature	(°C)	20	
Withdrawal velocity of mold	(cm/h)	5	3~50

Experiment

Procedure

The melting and casting were made in vacuum using the ceramic shell molds shown in Fig. 1. The pressure was less than 5×10^{-4} Torr and the melting stock was Rene 80, whose chemical composition is shown in Table II.

Table II. Chemical Composition of Rene 80 (wt%)

C	Mn	Si	Cr	Ni	Co	Fe	Mo	W	V	Ti	Al
0.17	0.10	0.10	13.9	bal	9.4	0.05	3.92	3.91	0.10	5.02	2.96
B	Zr	Nb	Ta	Hf	Mg						
0.014	0.03	0.10	0.10	0.10	0.01						

The casting temperature was 1500°C (210°C superheat) and the mold temperature before casting was fixed at 1440°C at the height of 5 cm from the chillplate. Temperature was measured with a platinum thermocouple set on the outer wall of the mold.

Detection of the Location of the Solidification Front

The location of the solidification front was detected by a direct measurement of the casting temperature. The shape of the front was observed by dropping 1 mm diameter tungsten particles into the molten metal (W tracer method), followed by quenching, sectioning and etching.

The Results of the Calculation and Discussion

Comparison With the Experimental Values

Fig. 2 shows the measured and calculated values at the withdrawal velocity of 10 and 20 cm/h. The measured temperature is somewhat higher than the calculated value in the low-temperature parts and vice versa in the high-temperature parts.

The difference between the measured values and the calculated ones is attributed to the uneven temperature distribution in the susceptor, which was disregarded in the calculation.

Fig. 3 shows the temperature gradient ahead of the solidification front when the mold temperature was changed.

The temperature gradient increases linearly in proportion to the heating temperature in agreement with the measured values. Thus, in order to increase the temperature gradient it is effective to raise the mold temperature.

In Fig. 4 are shown the effects of the withdrawal velocity of the mold on the temperature gradient. On calculation the gradient is almost constant up to the withdrawal velocity of 20 cm/h but at 50 cm/h it suddenly decreases at the points of 10 and 15 cm from the chillplate.

Fig.2 Example of calculated temperature distribution

At 40 cm/h the measured value is different from the calculated one. This is because the temperature was measured outside the mold, and when the withdrawal velocity is high, the difference of the temperature between the mold and the center of the castings becomes large and the temperature gradient appears to be larger than in the actual state. But when the withdrawal velocity is less than 20 cm/h, the calculated value agrees well with the experimental value.

Fig.3 Effect of susceptor temperature on the temperature gradient of castings

Fig.4 Effect of withdrawal velocity on the temperature gradient of castings

The Effect of the Casting Shape on the Temperature Gradient

In Fig. 5 and Fig. 6 the change of the temperature gradient with the progress of solidification is illustrated. In Fig. 6 is shown the change of the thermal gradient when the susceptor temperature was changed from 1350°C to 1800°C.

At the point of section enlargement, namely at the distance of 8 cm from the chillplate, the temperature gradient abruptly decreases. The decrease is larger for higher susceptor temperature. In Fig. 5 the withdrawal velocity is changed, where the same tendency as in Fig. 6 is observed.

Up to the withdrawal velocity of 20 cm/h the curves are nearly identical with each other. Low gradient appears only at 50 cm/h.

Fig.5 Calculated results of temperature gradient distribution in the castings (effect of withdrawal velocity)

Fig.6 Calculated results of temperature gradient distribution in the castings (effect of susceptor temperature)

The Cooling Effect of the Chillplate

Fig. 7 shows the change of temperature gradient by apparent heat transfer coefficient between the castings and the chillplate. Even the most powerful chill exerts influence only up to the height of 5 to 6 cm.

Fig. 8 shows the location of the solidification front under the same condition.

The mold was withdrawn at a constant velocity as represented by the straight line. The location rises up to 5 to 6 cm from the chillplate in the first 30 to 40 minutes and after that the progress of solidification is very slow, until the withdrawal catches up. This means that the chillplate is effective in slowing the solidification speed in the selector as well as in increasing the temperature gradient. This is considered to be one of the factors affecting the single crystal formation in the selector.

Fig.7 Cooling ability of chillplate

Fig.8 Location of solidification front vs the time elapsed

The Shapes and Location of Solidification Front

Fig. 9 shows the shapes of solidification front obtained by calculation. The location of the solidification front is 9 cm distant from the chillplate. Up to the withdrawal velocity of 10 cm/h the shape is convex, and at a higher velocity, it becomes concave. This is because the position of the solidification front deviates downward when the withdrawal velocity is high. (Fig. 12) When the location of the solidification front is outside the suscepter, the mold is cooled from outside, which brings about solidification from the mold wall and hence, a possibility of new crystal formation.

Fig.9 The shapes of solidification front obtained by calculation

This is why it is necessary to keep the position of the solidification front always within the susceptor by controlling the withdrawal velocity and susceptor temperature.

Fig. 10 is the shape of solidification front obtained by the tungsten tracer method. The shape is slightly convex and agrees with the calculated results.

Fig. 11 and Fig. 12 show the relation of the location of solidification front to the mouth of the susceptor with the progress of solidification, calculated by changing susceptor temperature and withdrawal velocity. The higher the susceptor temperature, the nearer it comes to the mouth.

Fig.10 The shape of solidification front obtained by tungsten tracer $v = 5 \text{ cm/h}$

When the withdrawal distance is short, the location stays completely in the susceptor by the cooling effect of the chillplate. When the withdrawal distance is 10 cm, the location again begins to come into the susceptor. We think this is because radiation from the surface of the mold outside the susceptor has a cooling effect as the mold is withdrawn. It is due to the shape of the sprue that the location comes near the mouth at the end of the process.

As to the withdrawal velocity, when it is 5 to 10 cm/h, the solidification front is within the heating zone, but when it is 20 cm/h, the position of solidification begins to deviate toward the outside and when it is 50 cm/h, it is completely outside the susceptor.

This explains the degradation of the temperature gradient at the point of 50 cm/h in Fig. 5.

Fig.11 Change of solidification front vs susceptor temperature

Fig.12 Change of solidification front vs withdrawal velocity of mold

In Fig. 12 the experimental points were obtained by direct measurement of the casting with a thermocouple and by the tungsten tracer method. Qualitatively they agree with the calculated results, but as they are few in number, it will be necessary to make further experiments.

At present a study of solidification calculation is in progress, in which radiation is directly taken account of. We are also studying NASAIR 100 alloy for single crystals, instead of Rene 80 which was used in this experiment.

Conclusions

From the result of our analysis the following conclusions about heat control of the growth of single crystals have been obtained.

1) When the withdrawal velocity of mold, which is nearly equal to solidification speed, is slow, the solidification front is convex, and when the velocity is high, it becomes concave. The former is favorable for the growth of single crystals. The tungsten tracer method proved useful for the observation of the shapes of solidification front.

2) The calculated temperature gradient in the liquid ahead of the interface increased in proportion to the heating temperature of mold above liquidus, and the experimental values agreed well with the calculated values.

3) The temperature gradient decreases at an enlarged section and the position of solidification front deviates toward the outside of the susceptor.

4) On calculation the values of temperature gradient decrease abruptly when the withdrawal velocity exceeds a limit.

5) The effective cooling range of chillplate within the castings is only 6 cm in height.

Thus, quantitative understanding of thermal aspects of unidirectional solidification using mold withdrawal method was significantly advanced. It contributes to more efficient control of solidification of both columnar and single crystal of superalloy.

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