MILITARY TECHNICAL COLLEGE

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CONTROL OF DIRECTIONAL SOLIDIFICATION PROCESS FOR PRODUCTION OF GAS TURBINE BLADES.

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ABSTRACT

One of the most recent methods of producing gas turbine blades is by controlled directional solidification of superalloys.The shape and orientation of the solidified phases,which determine the required mechanical behaviour of the blades are controlled by the growth conditions. These conditions are mainly the shape,position of the solid front as well as the growth rate (R) and temperature gradient (G).The parameter G/R determines the type of structure and a minimum(or critical) value should be obtained according to the alloy composition.
In the present work,the growth conditions are determined using numerical simulation of heat flow during solidification.A two dimensional heat flow model was set and solved numerically using a finite difference technique.The effect of the process variables:withdrawal speed,furnace temperature,starting baffle position,heat resistance at metal-chill interface on the growth parameters are studied.The conditions for obtaining a high G/R value are found.The computer program was used to find the suitable conditions to reduce the total solidification time and to reduce large variations in growth conditions.

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INTRODUCTION

Todays jet turbines are characterized by an about 40 % improvement of total effectivity compared with gas turbines of the sixties(1).This remarkable gain was partly accomplished by selection of superalloys,but mainly by cooling techniques of blades·Vacuum melting of alloys and precision casting together with optimization of microstructure has led to a jump in working temperature of a few hundreds degrees K and in reaching a high fatigue resistance at both high and low temperatures. In the seventies,the limits for improving a conventional cast or forged superalloy was reached through development of alloys with Cr,Mo and other solid solution hardeners consisting of γ' precipitates,which results in outstanding mechanical properties at high temperatures and hot gas corrosion resistance(1). Directional solidification(DS) of superalloys was the next step in an attempt to reach better creep resistance by avoiding grain boundries along the axis of the blade.Remarkable progress was made by introducing DS in investment casting technology.Some jet turbines already apply directionally solidified superalloys for blades and stator vanes.DS as an advanced casting technology was optimized to form composites of extremely fine distribution of fibres with a high aspect ratio.Such an evenly distributed fibres reinforced composite could hardly be produced by mechanical manipulation.
In order to optimize the DS process two steps have to be followed:first,laboratory experiments in order to optimize the structure,crystallographic orientation,segregation,etc,and to determine the critical functions which give the required structure, second,to make a numerical simulation model for solidification taking into consideration the process parameters in order to design the apparatus and process parameters.
In the present work,a numerical simulation model for solidification in non-uniform moulds is made in order to relate the process parameters(withdrawal speed,position of baffle,furnace temperature,etc.)to the growth parameters(growth rate,temperature gradient,interface shape).A further step is made to optimize the process parameters.The alloy used is the IN939 superalloy which is a strong highly corrosion resistant alloy.The alloy is highly used for vanes and blades in gas turbines(2).

NUMERICAL MODELLING

The modelling oriented itself by a set-up sketched in Fig.1(a). As a two dimensional model requires less computing time and is less complicated than a 3-dimensional model,the turbine blade shape was simplified and reduced to a cylindrical shape with a variable cross section,Fig.1.The model is based on the solution of the heat flow differential equation

$$c\rho\, dT/dt=k\, d^2T/dX^2 +k\, d^2T/dZ^2 +L(df_s/dT)dT/dt \qquad (1)$$

where k,c and ρ are thermal conductivity,specific heat and specific gravity respectively,L,latent heat of fusion,T,temperature,t,time,f_s,fraction solidified in the mushy zone.

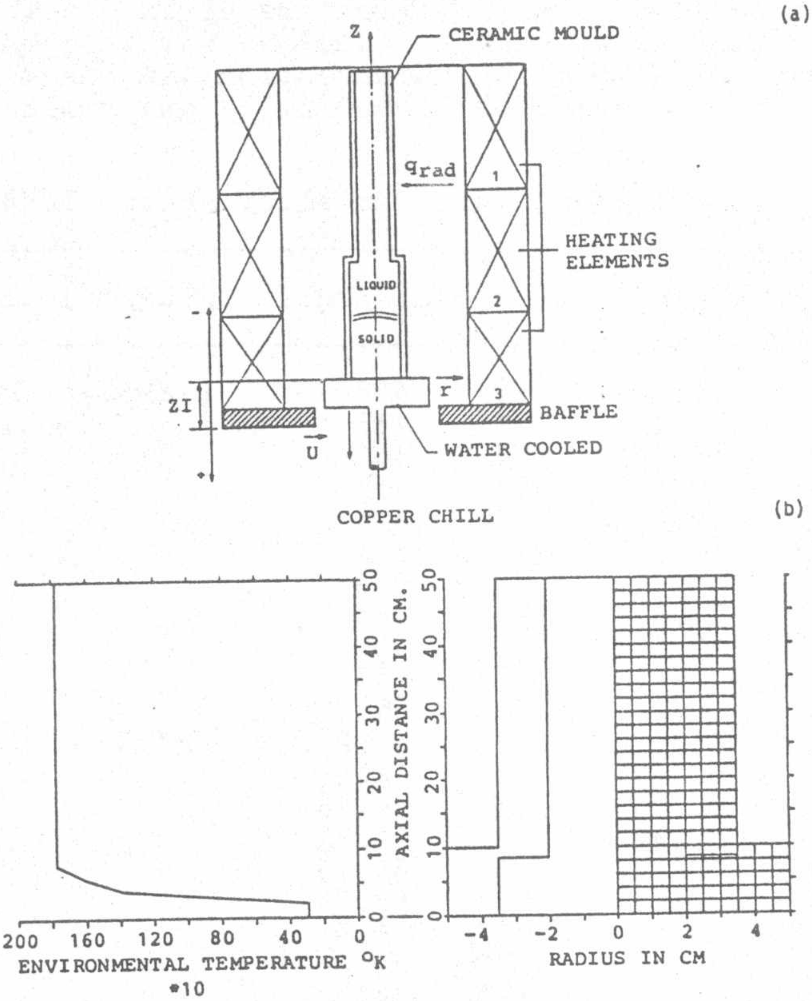


Fig.1.The experimental set-up shows the relative location of mould to heater,baffle and copper chill (a)Environmental temperature distribution along the mould is indicated for time t=0 position simultaneously illustrating the metal-and-mould-half-enmeshment(b).

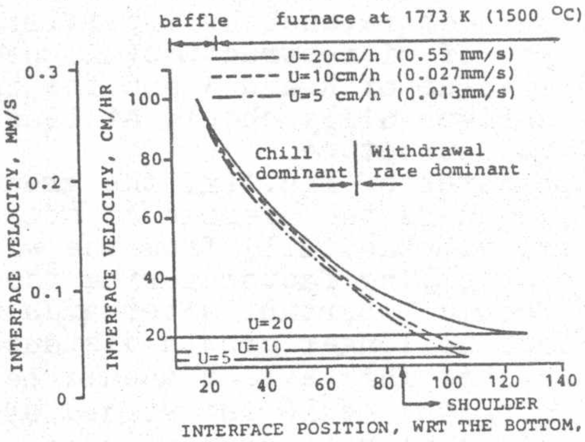


Fig.2.The effect of withdrawal rate U on the rate of advance of the interface as the interface is moving away from the chill.It varies noticeably with U.The baffle position is indicated on the figure.

The model is solved using the explicit finite difference method. The details of the model and solution are given elsewhere(3). Fig.1(b) shows the mould shape as enmeshed within metal and mould for numerical simulation.No convection was assumed in the liquid.The thermophysical data of the alloy and mould are given in Table 1.

Table 1. Thermophysical data for alloy and mould(4-6)

	T(K)	k(W/mK)	T(K)	c(J/kgK)	ρ(kg/m^3)	L(J/kg)
alloy IN939	293	11.3	293	416	(293K)	8074
	373	12.6	373	435		
	473	14.2	473	460	8160	T_L =
	573	15.6	573	485		1585K
	673	17.1	673	610		T_S=
	773	18.5	773	534		1526K
	873	20.0	873	559		
	973	21.5	973	583		
	1073	22.9	1073	608		
			1173	633		
			1273	658		
invest-ment mould	293	0.399	323	49.2	2750	
	373	0.342	373	52.9		
	473	0.284	473	59.15		
	573	0.246	573	61.7		
	673	0.217	673	65.75		
	873	0.177	873	68.7		
	1073	0.153	1073	71.9		
	1273	0.143	1273	74.2		
	1573	0.136	1573	76.7		
	1873	0.131	1573	79.6		

EFFECT OF PROCESS PARAMETERS ON GROWTH RATE(R) AND TEMPERATURE GRADIENT(G)

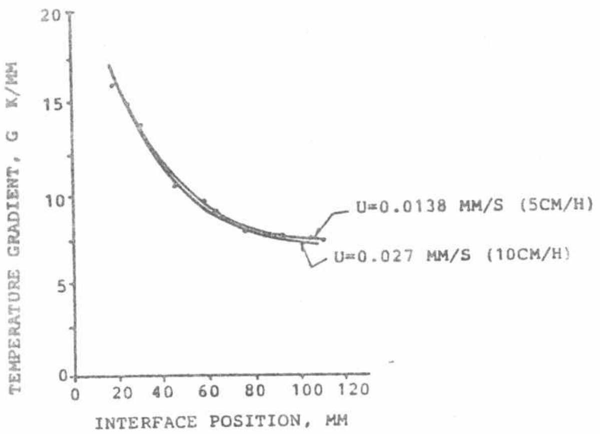
It has been shown by several investigations(7)that in steady state DS,the microstructural parameters,such as interfibre or or dendrite arm spacing,and type of microstructure(aligned,cellular,dendritic) depend on the value of R and G and the ratio G/R.A critical G/R ratio for a given alloy should at least be reached for obtaining an aligned structure.

Fig.2 shows that using the apparatus of Fig.1(a) the growth rate or interface velocity (R),taken as the average of solidus and liquidus velocities,differs substantially from the withdrawal rate U.The chill is the controlling factor during the first 70mm of growth while U does become important afterwards.moreover,the use of a higher U leads to longer growth distances before steady state growth is reached.This effect should be taken into consideration when designing the mould for steady state growth of turbine blades.Therefore,starter blas of same 10cm

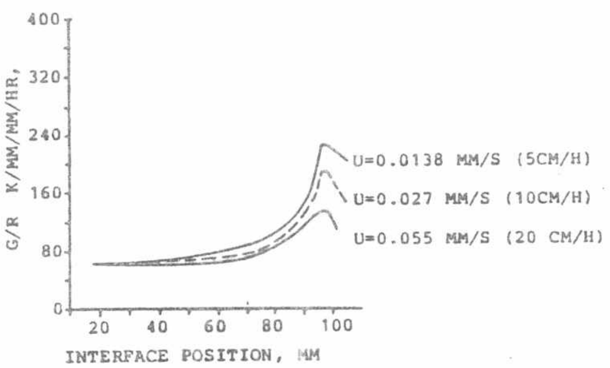
are being added to the blade base(8).
The temperature gradient in the solid/liquid interval decreases as growth proceeds, but is not sensitively affected by U, Fig.3 (a) while a difference in G/R is found, especially around the variation in cross section(shoulder), Fig.3(b).
The growth rate variations are found to be slightly affected by the heat transfer coefficient at the metal/chill interface Fig.4, but even more so by the relative position between chill and baffle, Fig.5. It is to be noted that the cross section variation of mould and casting did not affect the growth rate pattern, Figs.2 to 5; this is probably due to the strong chill effect and the reduction in cross sectional area rather than an increase in area(9-11). G was found to decrease as growth proceeds, Fig.6, and is higher for a higher furnace temperature, keeping the pouring temperature at 1673K. Fig.7 shows G/R values as growth proceeds for two different furnace temperatures. These results indicate that the G/R value increases as growth approaches the shoulder region of the blade. Further computations indicate that G/R will drop slowly to about its starting value after the shoulder is bypassed. Preliminary experiments on steady state DS of the superalloy IN939(12) have shown that aligned dendritic structure is obtained parallel to the withdrawal direction if a critical G/R 35(K/mm/mm/s) is reached. Fig.7 shows that the G/R values are higher than critical if the furnace temperature is 1773K. For a furnace temperature of 1673K this value is only reached after a growth distance of 60mm where the shoulder effect sets in.

EFFECT OF PROCESS PARAMETERS ON S/L INTERFACE SHAPE

The shape of S/L interface is mainly dependent on heat flow direction. An axial orientation of the phases is obtained if the interface is planar or slightly convex. A concave interface usually causes radial growth and nucleation of new grains at the mould wall, therefore destroying theDS structure. The shape of the interface was found to be directly related to U and to the initial positionbelow the baffle (ZI), Figs.8 and 9. At relatively slow withdrawal rates(up to 0.055mm/s) the interface is essentially planar at ZI=0. As U reaches 0.11mm/s the interface is slightly concave in the first 80mm, Fig.9. At a much higher speed 0.208mm/s, the interface decomes highly concave, even with an initial position of 40mm inside the furnace(above baffle), indicating a strong effect of radial cooling. However, this concavity can be hindered over larger solidified distances if the mould is pushed inside the furnace, i.e. ZI negative. A comparison between Figs.10(a) and(b) shows that more than 80mm could be solidified with a planar interface using U 0.208mm/s if ZI is -80mm.
In most cases there is a limitation for the mould location inside the furnace. Therefore, ZI has to be chosen in accordance with U in order to hinder radial cooling over the required growth length.



(a)



(b)

Fig.3.Effect of withdrawal rate on:(a) Temperature gradient G and (b) G/R vs. interface position

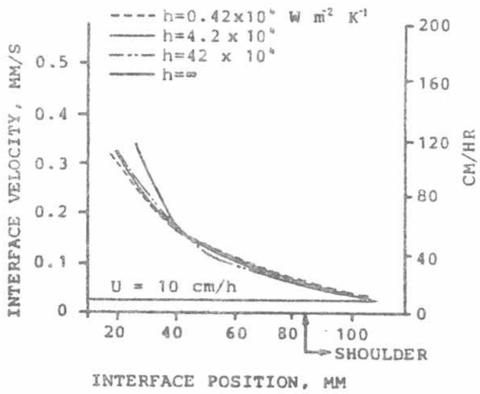
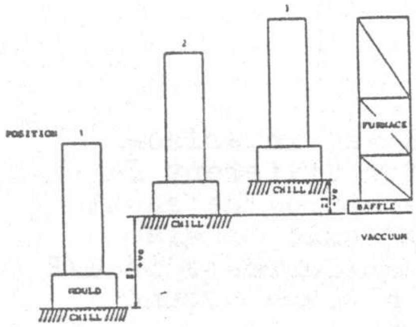
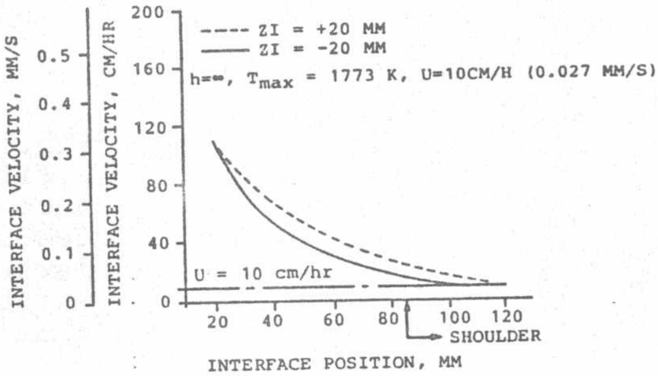


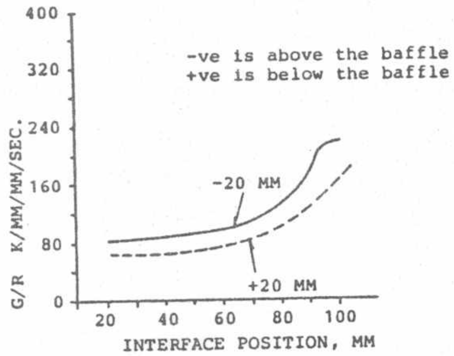
Fig.4.Effect of heat transfer coefficient at metal-chill interface(h) on interface velocity which becomes strong for large values of h. $U=0.0277 mm/s, T_{furnace}=1773K$.



(a)

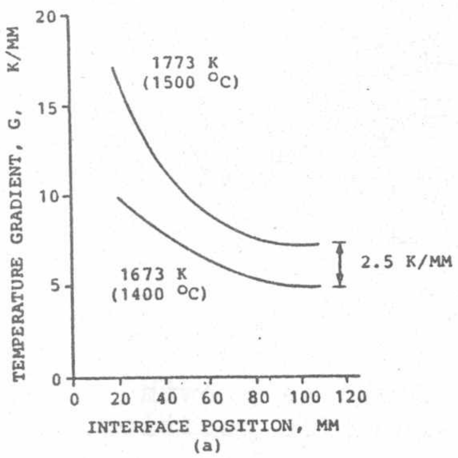


(b)



(c)

Fig.5.(a)The sketch shows the different initial mould positions wrt the baffle;(b) and (c)shows interface velocity and G/R vs. interface positions for two different initial positions wrt baffle;h= ,$T_{furnace}$ =1773K,U=0.0277mm/s.



(a)

Fig.6.Temperature gradient vs. interface position for two furnace temperatures 1673 and 1773K shows appreciable differences.

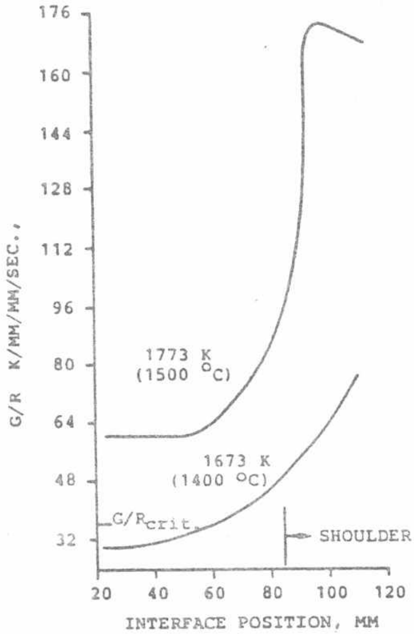


Fig.7. G/R vs. interface position for different furnace temperature. The shoulder in the mould is also marked as an increase in G/R which takes place around this region.

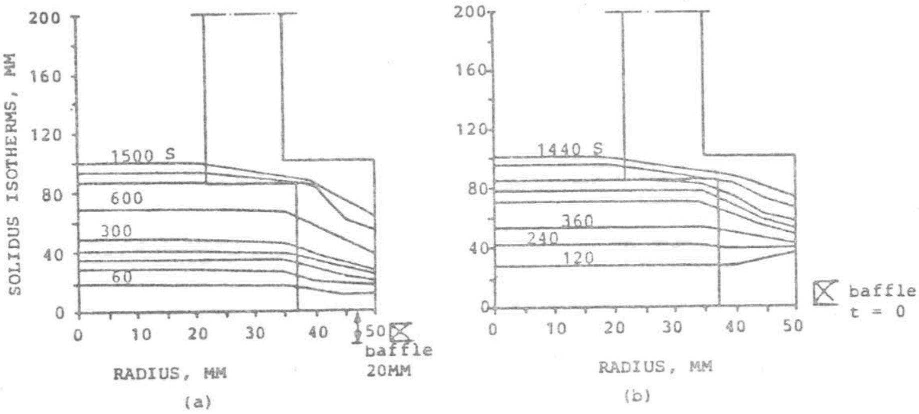


Fig.8. Solidus isotherms in metal and mould as growth proceeds showing the effect of initial baffle position.

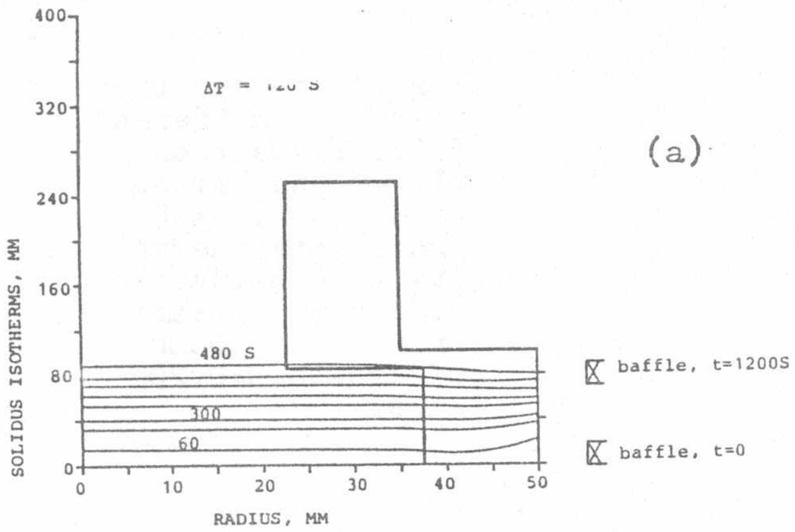
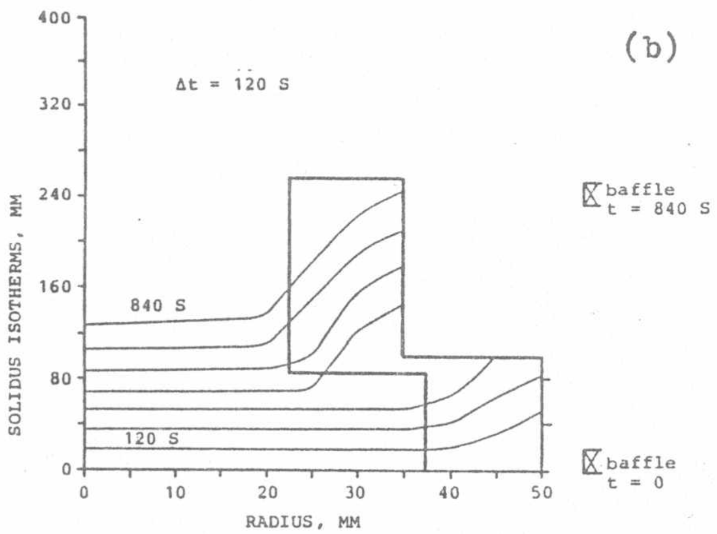
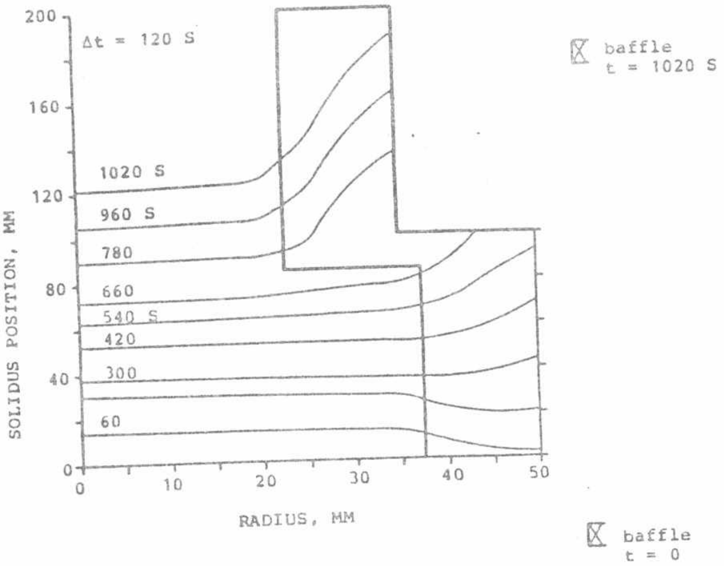


Fig.9.Solidus isotherms at 120s time interval for diffe- withdrawal speeds:
(a) 0.055mm/s
(b) 0.277mm/s
showing the concavity of the inter face at high speeds



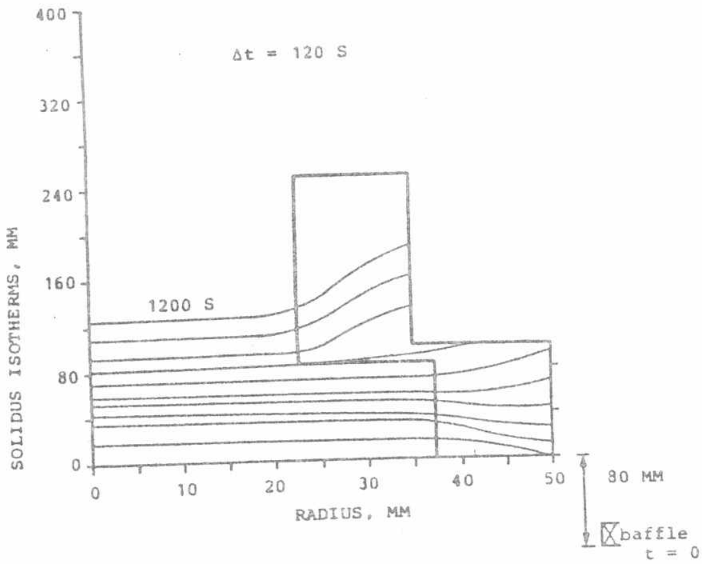
OPTIMIZATION OF PROCESS PARAMETERS

For a successful DS process,G/R should be greater than a critical value,a planar interface should be reached on the macroscale and the growth conditions should be as uniform as possible to obtain uniform structure.Moreover,the production time should be kept to a minimum for economical point of view.It can be noticed from Figs.3,5 and 7 that G/R is in most cases greater than the critical value.However,it has been proved that in end-chill specimens(13,14).The macro and microstructures are fine close to the chill and become coarser with the distance from the cooling plane.This would give non uniform mechanical and physical properties(15).The most simple remedy for this behaviour is to add a starter blas of a predetermined length which will cause a loss in material and time and afterall this length should be predetermined by several experiments.



(a)

Fig.10.Solidus isotherms at different initial positions ZI wrt the baffle (a)ZI=-40mm,with concave isotherms, (b)ZI=-80mm,where concavity appears only after 100mm of growth.U=0.208 mm/s.



(b)

In order to reduce the large variations in R,G and G/R,U was varied from 0.055 to 0.27 mm/s and ZI from 0 to -80mm.The results in Fig.11 show that an almost constant G/R is obtained for the conditions where U=45mm/s,ZI=-60mm and where U=0.11mm/s and ZI=-50mm.For these two conditions,the variations in R and G are minimal over a reasonable distance covering the effective length of the turbine blade,which should be correctly positioned according to these results.Table 2 gives the time elapsed and the length solidified for the different process parameters.From Fig.11 and Table 2,the optimum conditions could be determined. For uniform growth conditions and minimum time,U is 0.125mm/s ZI -60mm,which gives a solidified length of 125mm over an 1500s time period.The table also shows the position of the chill at the end of solidification.
The reduction of the mould thickness was expected to affect the growth behaviour inside the mould.In fact,decreasing the mould

Table 2.Total solidification time and end position for different process parameters

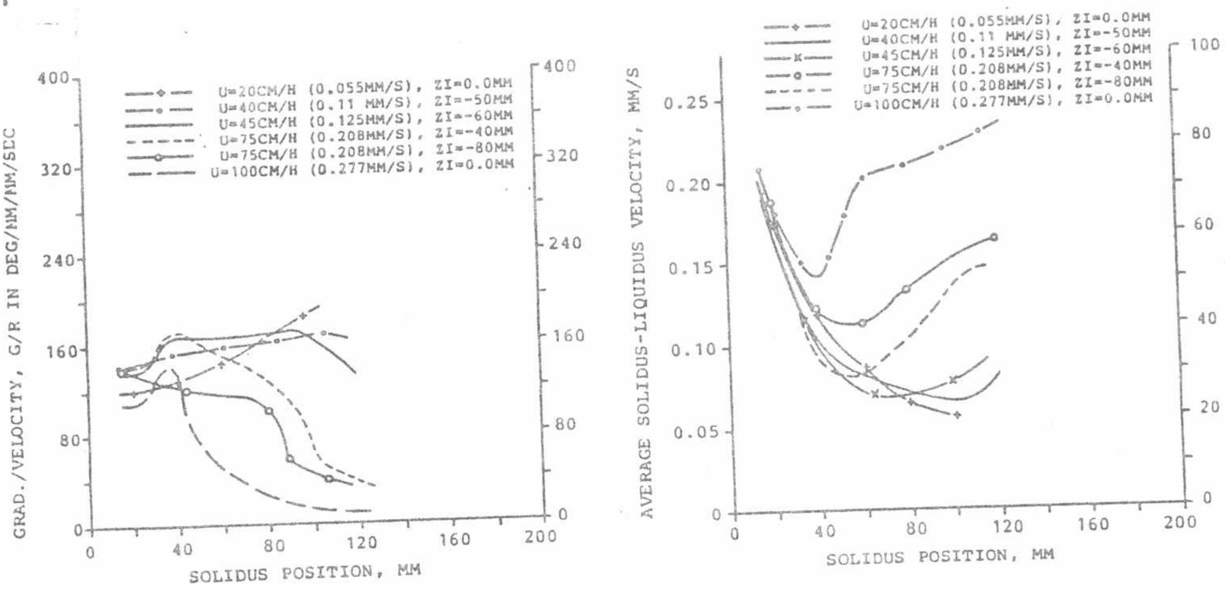
U(mm/s)	0.125	0.055	0.11	0.208	0.277
ZI(mm)	60	0	50	40	0
ZO(mm)	127.5	66.7	123.0	172.5	233.0
Time(s)	1500	1200	1560	1020	840
L(mm)	125	105	125	121	105

ZI =position of chill above baffle at time=0
ZO =position of chill below baffle at end of solidification
Time=time needed to solidify a length L

thickness from 13.5 to 7.5mm did affect R,G and G/R as shown in Fig.12.The growth rate slows down which is reflected on a higher and almost constant G/R value.Under these conditions the metal is more sensitive to the surrounding thermal conditions.An improvement in solidification conditions was previously observed by reducing mould wall thickness(11).
A withdrawal strategy was tried out.It consists of keeping the mould stationary until the interface reaches 30mm above the chill after which a withdrawal rateof 0.11mm/s is applied.This results in slowing down R as shown in Fig.13(a) while G is slightly higher. Increasing the furnace temperature was found to raise G and slow down R,Figs.6 and 7.In the following,the metal is poured at 1773K,the furnace is kept at the same temperature except the lower heater which will be adjusted to give 1873K.This is shown by the environmental temperature distributions in Fig.14(a).The results in Fig.14 show that by increasing the lower winding temperature R slows down and G increases so that a much higher G/R value is obtained($250X10^2$K/mm/mm/s) compared with another condition keeping all the windings temperature constant at 1773K. The drawback for this method is that a high gradient will be acting on the lower heater and on the ceramic mould which implies special precautions

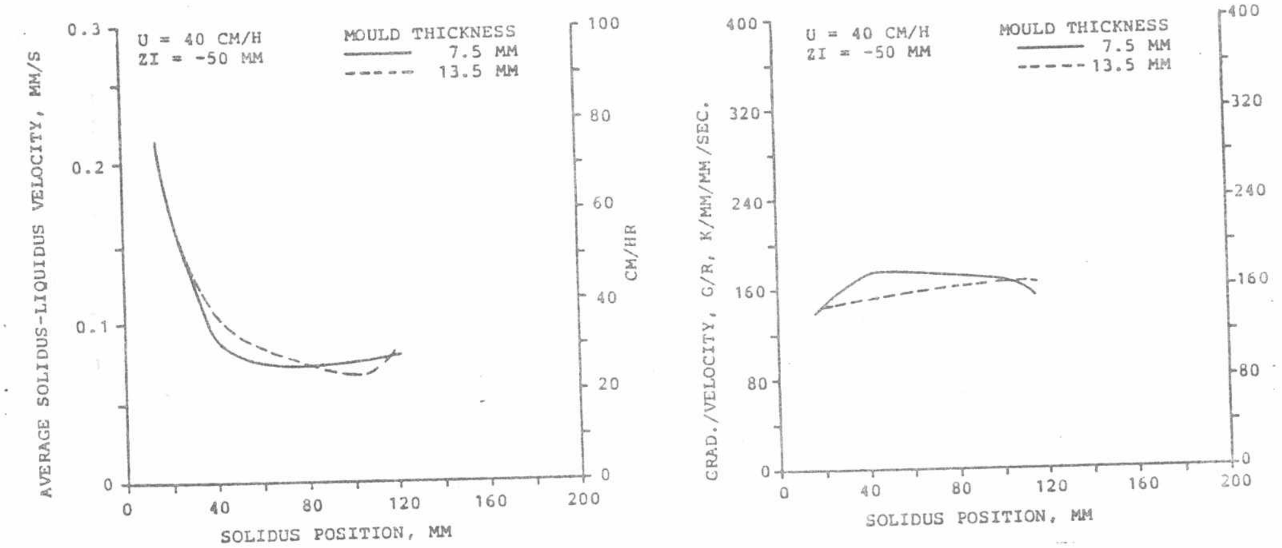
CONCLUSIONS

These results clearly indicate in agreement with much earlier experimental evidence,how numerical simulation of solidification can be useful in preestimating growth behaviour.It thus may save material costs and time that could be lost in performing a lot of trial experiments.Thus,also design of the apparatus and the processing variables can be predetermined using such numerical simulation.



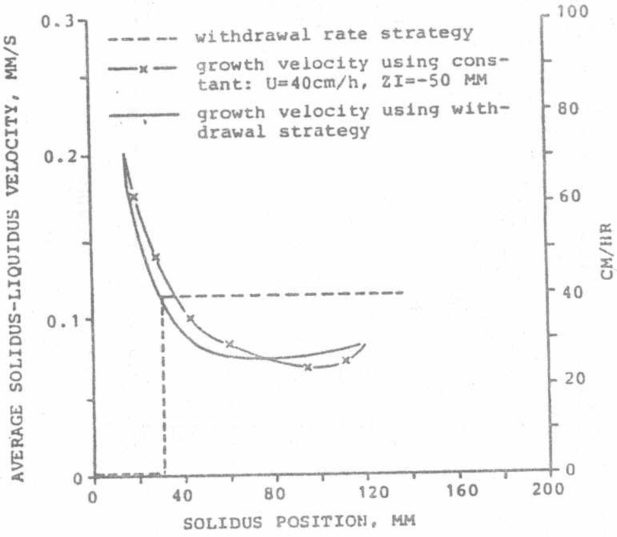
(a) (b)

Fig.11.Different U and ZI combinations are tried in order to reduce variations in growth parameters R,G and G/R.The effect is shown on (a)R and (b)G/R .

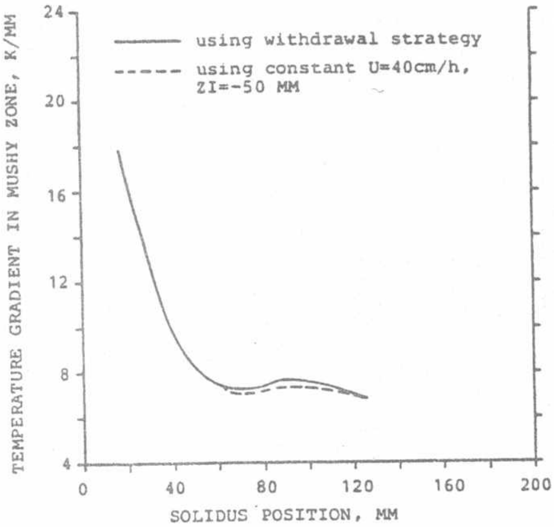


(a) (b)

Fig.12.Effect of decreasing mould thickness on (a)R and (b)G/R,which indicates that higher G/R values could be reached with thinner moulds.



(a)



(b)

Fig.13.The withdrawal strategy and its effect on:a)R and b)G.

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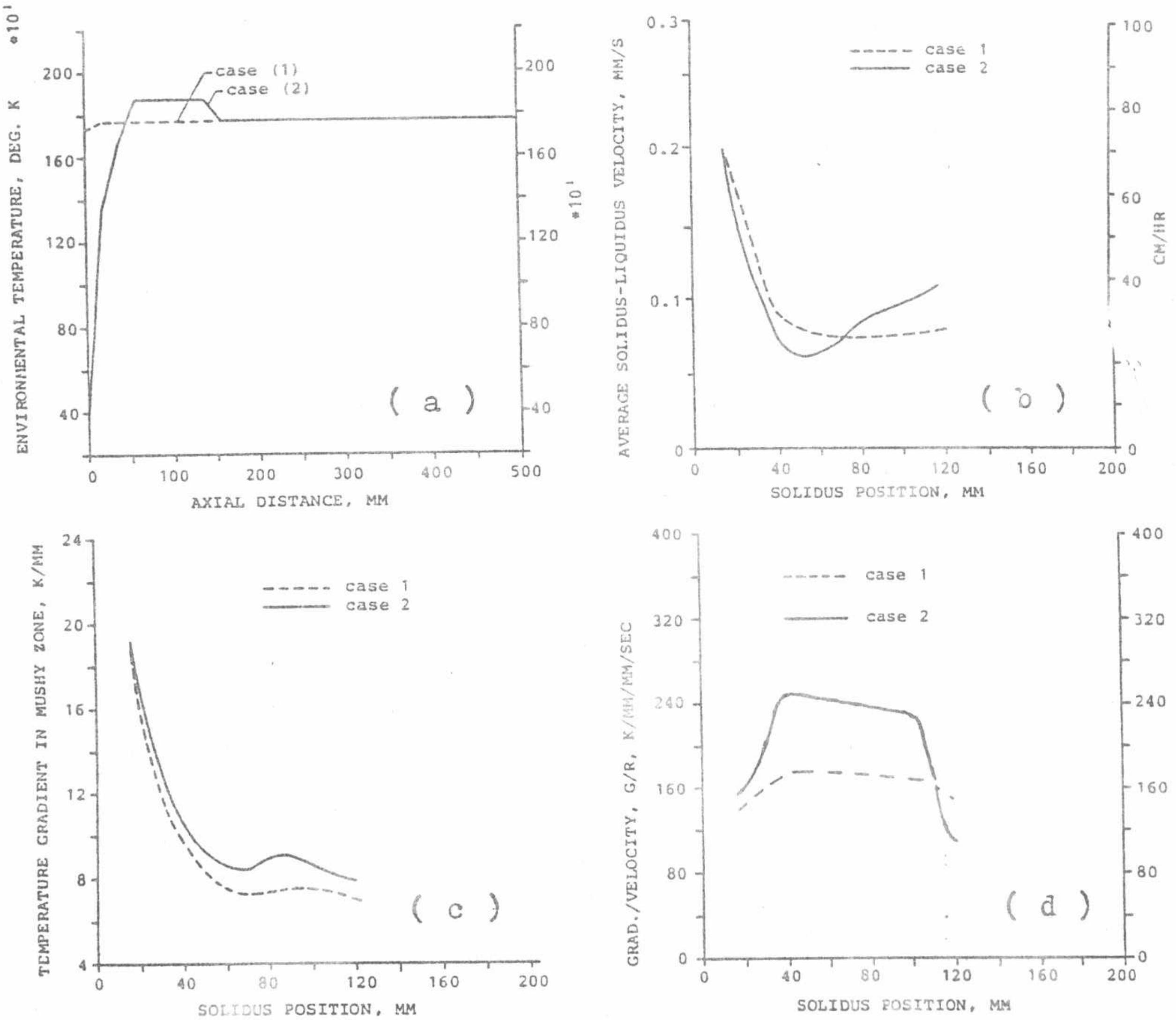

Fig.14.Effect of raising the lower heater temperature (a) on growth parameters:(b) R,(c) G and (d) G/R.Mould thickness 7.5mm,U=0.11mm/s.

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