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An experimental investigation into the formation of an equiaxed zone in ingot casting: Pb–Sb alloy system

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An experimental investigation was undertaken to obtain a better understanding of the phenomenon of equiaxed zone formation in ingot castings with particular attention to the thermal conditions during dendritic growth and the mechanism of columnar-to-equiaxed transition. Thermal conditions during dendritic growth were measured in the laboratory-scale Pb–Sb castings. Solidification was also directly observed in castings of the cyclohexanol–phenol red system. A close correlation was noted between the general behaviour of the thermal history curves, especially when taken on the centreline of the ingots, and the resulting macrostructure. The dendritic solidification front was found to grow with considerable solute undercooling and also with a slight, but positive, temperature gradient ahead of the front in the bulk liquid. Moreover, the dendritic front temperature was also noted to increase with distance from the mould wall surface, the nominal rate of advance of the front being sensitive to the solute content and the cooling rate. Heterogeneous nucleation ahead of the columnar front was believed to have played a major role in equiaxed zone formation. However, columnar-to-equiaxed transition was observed not to take place immediately when the equiaxed crystals formed, but some time later, equiaxed dendrites growing at a somewhat higher temperature than the columnar dendritic front. Finally, combining the information gained from thermal analysis data with the observations made upon non-metallic castings, a novel picture of how columnar-to-equiaxed transition takes place has been proposed.

1. Introduction

In the study of the structure of ingot castings, the phenomenon of columnar-to-equiaxed transition (CET) has gained considerable attention. The significance of CET has been treated in several articles (e.g. [1, 2]). It is known that for CET to occur, equiaxed crystals must somehow originate and then these have to grow to a sufficiently large size.

There are at least four theories on the formation of equiaxed crystals:

1. the constitutional supercooling theory [3] maintains that the equiaxed crystals nucleate after the columnar zone is formed, as a result of the constitutional supercooling of the remaining liquid;
2. Chalmers [4] introduced the possibility that all the crystals originate during the initial chilling of the liquid layer in contact with the mould (big-bang mechanism);
3. Jackson *et al.* [5] and O'Hara and Tiller [6] suggested that a remelting mechanism of the dendrite arms is responsible for the formation of the equiaxed zone; and
4. Southin [7] suggested that dendrite branches dislodged from the free surface of the melt are responsible for the equiaxed crystal formation.

Many studies have identified all these mechanisms occurring provided the appropriate experimental conditions existed [8].

Growth of equiaxed crystals, as well as how CET occurs, have been much less considered.

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Reports on temperature measurements [9, 10] and of chemical analysis of dendrite centres quenched at some stage during solification [11, 12] reveal that both columnar and equiaxed dendritic growth proceeds with some undercooling at the tips. However, controversies exist in the literature regarding thermal conditions during dendritic growth. It is generally agreed that irrespective of the resulting macrostructure, the dendritic solidification front in ingot castings advances at a constant temperature and with almost zero temperature gradient ahead of it. Actually, in a casting where growth is purely columnar dendritic, growth conditions are expected to vary continually during dendritic growth and this must, as Burden and Hunt [13] demonstrated on undirectional growth experiments, also be accompanied with the alteration of the dendritic tip temperature. On the other hand, in castings where growth is columnar–equiaxed or fully equiaxed, latent heat that is released from the equiaxed dendritic growth must be removed out of the casting through the dendritic solidification front, therefore the latter will be expected to grow at a lower temperature than the crystals growing nearer to the centreline of the castings, in order to provide heat flow.

It has been demonstrated that CET does not take place immediately the temperature of the bulk liquid falls to a rather constant level, but some time later [14]. There is ample evidence that CET occurs only if the liquid ahead of the columnar interface can be constitutionally supercooled [15] and also that the extent of equiaxed zone increases with constitutional supercooling parameter [16]. In fact, recent work by Witzke *et al.* [17], attempting to model the composition and temperature fields ahead of the columnar front, demonstrates that constitutional supercooling within the thermal boundary layer ahead of the columnar front may well be at the origin of CET. It is certain that constitutional supercooling ahead of the columnar front reaches its maximum very early during solidification, then the question of "how can the columnar front grow at a considerable distance from the mould surface?" still remains unanswered. Unfortunately, a clear picture of how CET occurs has not been developed. An early, widely accepted view is that CET results from independent growth of columnar and equiaxed crystals, so that columnar growth halts when its front impinges upon the sluggish liquid of equiaxed dendrites [18]. A counter argument favours two different modes of equiaxed zone formation; one growing by sedimentation of free crystals upon the vertically growing columnar front and the other developing by attachment of free crystals individually upon the horizontal dendritic interface [19]. This proposal has been based upon work on the NH_4Cl–H_2O system. A similar mechanism of equiaxed zone formation has also been proposed on the basis of studies including metallic alloys [14]. More recently, Burden and Hunt [20] have also suggested independent columnar and equiaxed dendritic growth processes in ingot castings where CET was presumed to occur catastrophically, resulting from the thermal conditions developing in the casting.

The present work was undertaken to investigate experimentally the columnar–equiaxed transition in laboratory-scale castings. A major portion of the work was confined to the search for a probable correlation between the thermal conditions during dendritic growth and the resulting macrostructure. The second phase of the work consists of direct observation of solidification process on the cyclohexanol–phenol red system. The latter has long been recognized to solidify in a fashion similar to metallic alloys [21] but there exists no record of evidence that it has been used in the past.

It is believed that the outcome of this work helps to resolve much of the controversy listed above and also to develop a novel picture of columnar-to-equiaxed transition in ingot castings, at least on the laboratory scale.

2. Experimental details

In metal alloy castings, the base metal was lead of of 3N7 purity. As solute, initially high purity and subsequently commercial grade antimony was used. An *in situ* solidification technique was employed, where ingots were solidified in a mild steel cylindrical mould with a graphite-coated inner surface. The mould dimensions were 110 mm inside height, 6 mm wall thickness and a general inner diameter of 76 mm, while providing a 1° taper for easy ingot removal. Thermal history curves from different locations of ingots were obtained using chromel–alumel thermocouples sheathed in 1.2 mm diameter close-end alumina tubes. Thermocouple sheets were suspended in the castings through an asbestos mould lid in order to minimize heat conduction through them. A rotating switch system, connecting the thermo-

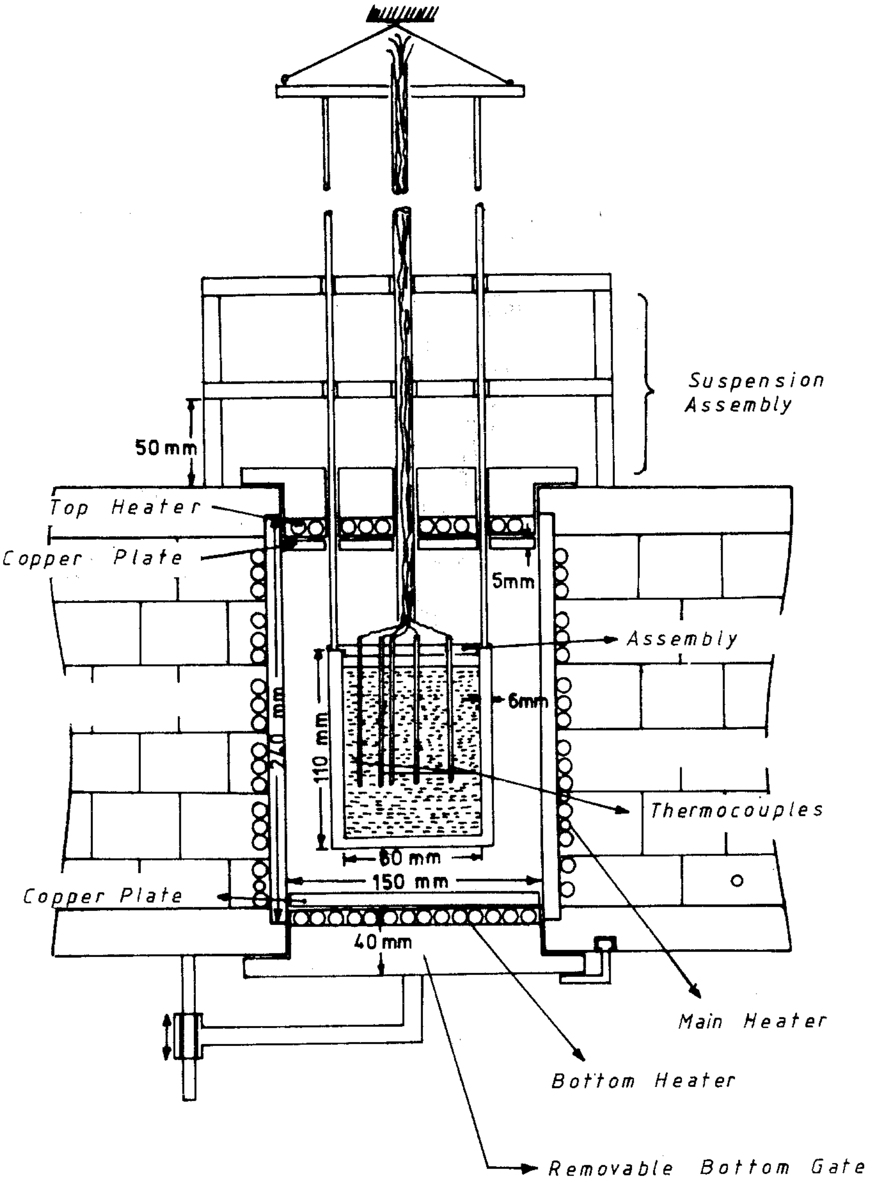

Figure 1 Heating system in order to obtain homogeneous temperature distribution within castings prior to solidification.

couple ends to a two-pen x–y recorder enabled the use of up to seven thermocouples simultaneously. The most sensitive range of the recorder was 0.1 mV, therefore, temperature differences as small as 0.25° C between locations could be easily read. Casting procedure was as follows: the required alloy was melted, well stirred and transferred into the casting mould, which was then maintained at the usual preheating temperature of 350° C (in order to attain thermal homogeneity throughout the melt) in a specially designed resistance furnace, as schematically illustrated in Fig. 1, and subsequently allowed to cool by sliding the mould down the bottom opening of the furnace. Different cooling rates were attainable by allowing the ingots to solidify in still air, by blowing air or water upon it at variou rates through a perforated cylindrical device. In addition to these, a three-part mould was also constructed, as shown in Fig. 2, in order to be able to rapidly quench the central portion of the castings at some stage during the solidification process.

Castings of the cyclohexanol–phenol red system were made in a perspex sided, U-shaped copper mould, as illustrated in Fig. 3. The perspex sides were double walled, being separated by

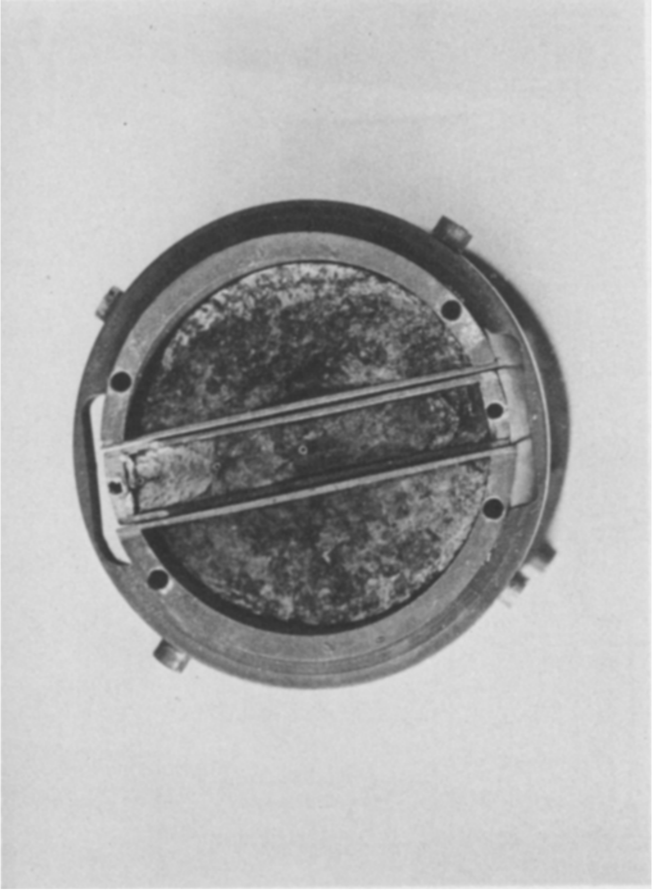

Figure 2 Three-part ingot mould (top view).

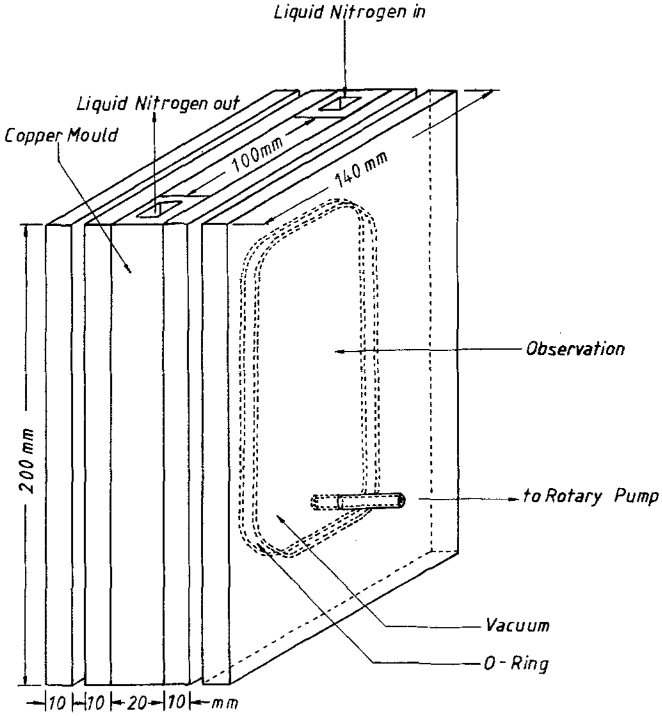

Figure 3 A sketch illustrating the perspex sided, U-shaped, double walled copper mould employed for non-metallic castings.

TABLE I Data collected from temperature measurements through a single thermocouple inserted centrally into the castings

Nominal solute content (wt% Sb)	$(\mathrm{d}T/\mathrm{d}t)_l$ (°C sec^{-1})	T_a (°C)	T_{max} (°C)	Equilibrium liquidus temperature (°C)	t_2-t_1 (sec)	Nominal dendritic front growth velocity (mm sec^{-1})	Ingot structure
2.25	0.360	309	310	312	114	0.333	Coarse columnar
2.25	0.960	209	310	312	66	0.575	Coarse columnar
5	0.340	286	287	294	57	0.436	Medium columnar
6.5	0.320	277	279	283	54	0.703	Medium equiaxed
8	0.320	269.5	270	272	39	0.974	Fine equiaxed
8	0.320	267.5	270	272	21	1.809	Fine equiaxed

O-rings and evacuated down to 0.01 mm Hg pressure in order to minimize heat conduction into the ambient through side walls. The copper mould was cooled by a constant flow of liquid nitrogen from a pressurized Dewar. Observations were made by means of a Zeiss binocular microscope with camera attachment.

3. Results and discussion

3.1. Thermal conditions during dendritic growth

The general behaviour of the thermal history curve obtained during solidification of an alloy of finite freezing range is well known [9]. Generally, initial undercooling is observed. Then recalescence is followed by a period of temperature arrest and then by continuously descending temperature during the remainder of growth of the primary solid phase. Finally, after some undercooling, the growth of non-equilibrium eutectic occurs at constant temperature. In the present work, interests were confined merely to the dendritic growth; therefore, only the corresponding portions of such curves are considered in this paper. Actually, good correlation was established between the thermal conditions prevalent during dendritic growth, when obtained from a location on the centreline of the castings and the resulting macrostructure. Typical examples are presented in Figs. 4a and b. For example, in a thermal history curve obtained from an ingot of fully columnar structure, initial undercooling is usually followed by a relatively long plateau period (Fig. 4a), while in a columnar–equiaxed or fully equiaxed structured ingot, a well-defined recalescence following the initial thermal undercooling was the characteristic of the thermal behaviour (Fig. 4b). Data computed from the thermal history curves collected from temperature measurements on the centreline of castings are presented in Table I, where $(\mathrm{d}T/\mathrm{d}t)$ is the rate of cooling of the casting prior to commencement of solidification: $t_2 - t_1$ is the plateau period (defined in this work as the time difference between end of plateau and the moment of thermal arrest); T_a the initial thermal undercooling temperature, and T_E the equilibrium liquidus temperature of the particular alloy under consideration. Thermal arrest on a cooling curve, as obtained in this work, is the stage of the solidification process at which the instantaneous rate of realease of latent heat of fusion exceeds the instantaneous heat withdrawal rate from the ingot. Since the former is determined by nucleation and growth rates, thermal arrest can be safely related to the nucleation event on the mould wall surface. Accordingly, the plateau periods presented in Table I must correspond to the approximate growth period of columnar dendrites in a fully columnar structured casting and also to the development period of dendrite skeletons from the mould surface to the centre in columnar–equiaxed or fully equiaxed structured ingots. In all these cases, the nominal rate of advance of the dendritic solidification front can be estimated by dividing the growth distance, in this work ingot radius, by the plateau period on the corresponding thermal history curve. Such has been made and the typical results are given in the final column of Table I. The data indicate under comparable casting conditions that the dendritic solidification front advances at a higher rate with increasing solute content and cooling rate. Furthermore, Table I also indicates, irrespective of the resulting macrostructure, that dendritic growth proceeds with some undercooling at the tips. Hunt and Jackson [22] have shown that kinetic undercooling is negligibly small. The method adopted by others [9] allows estimation of the extent of undercooling due to tip curvature. In the present work this may be at a maximum of 0.05° C for a tip

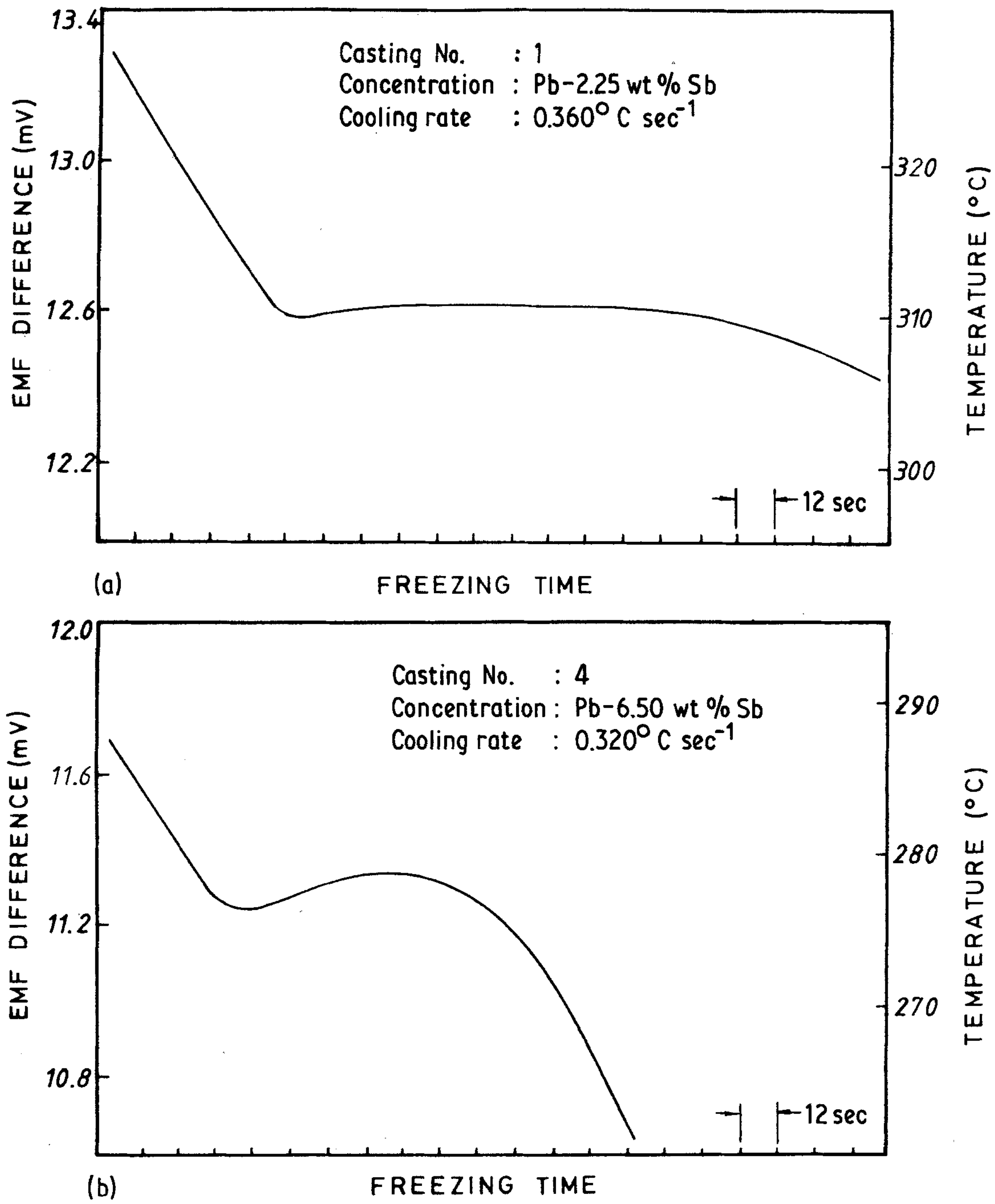

Figure 4 Comparison between the general cooling behaviour of the central regions of castings of (a) fully columnar, (b) fully equiaxed grain structure.

radius of, say, 1 μm, thus presenting a very small value. Consequently, apparent differences between T_E and T_{max} must owe their origins to the solute built up at the dendrite tips. Interrelations between dendrite tip undercoolings and the casting parameters such as solute content and cooling rate are also known [9, 13]. Accordingly, faster columnar dendritic growth velocities resulting from higher values of these parameters must have their origin at the increased solute undercooling at the tips. However, in fully equiaxed castings, highly possible effects in measuring shorter plateau periods at higher values of solute content and cooling rate should be the increased population density of

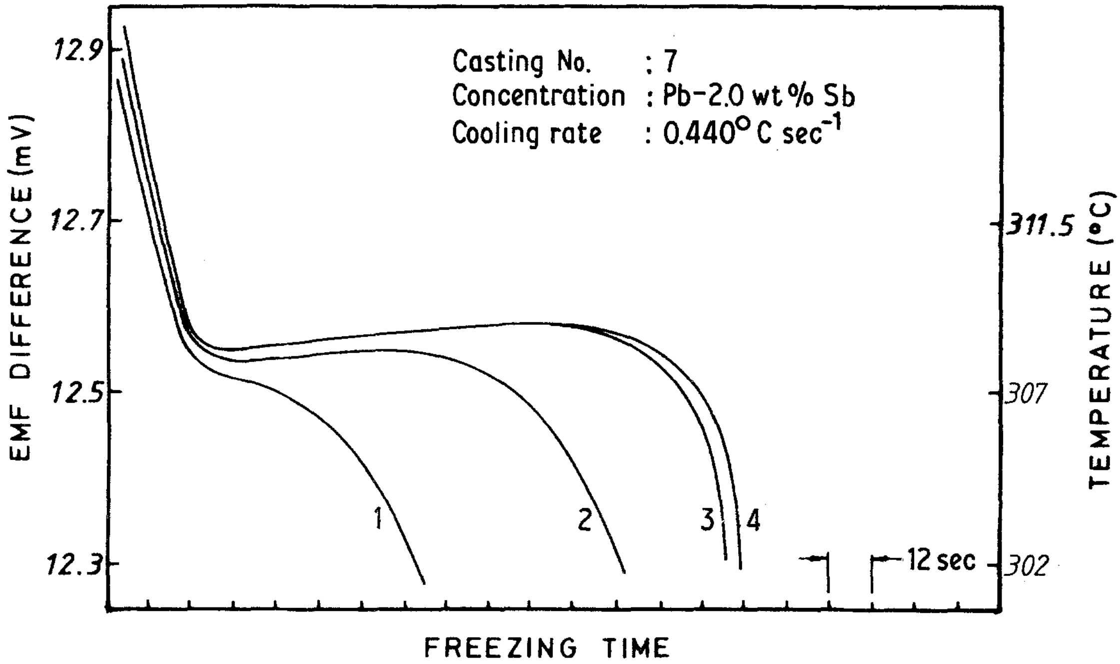

Figure 5 Thermal conditions existing radially during the dendritic growth stage of a fully columnar ingot.

equiaxed dendrites at higher values of these parameters, in addition to faster dendritic growth.

Thermal history curves have also been simultaneously gathered from temperature measurements at different locations of castings. Thermocouple readings were subsequently corrected with respect to differences in readings in the thermally homogenized melt prior to solidification. Typical curves are presented in Figs. 5, 6a and 7, corresponding to ingots of columnar, columnar—

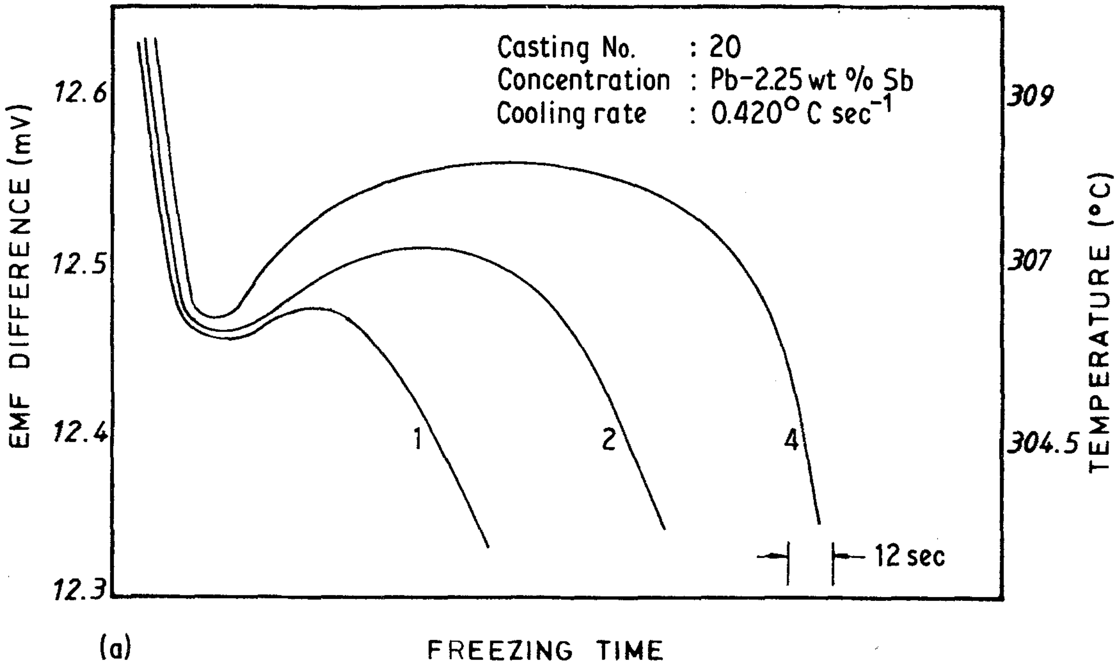

Figure 6 (a) Thermal conditions existing radially during the dendritic growth stage of a columnar–equiaxed ingot; (b) corresponding ingot structure.

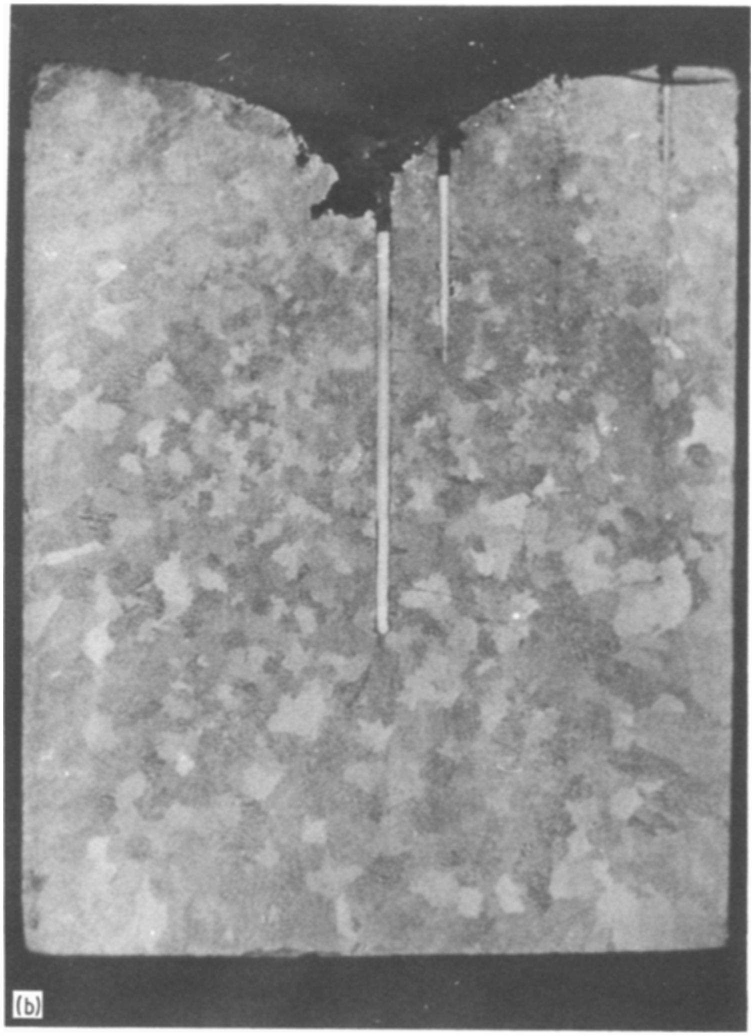

Figure 6 Continued.

equiaxed and fully equiaxed structures, respectively. In these figures, cooling curves 1, 2, 3 and 4 have been obtained by locating the thermocouples at distances 7, 19, 32 and 38 mm from the inside mould surface, the thermocouple tips being held at mid-ingot height. In such a collection of thermal history curves, the passage of the dendritic solidification front through any location can be followed by the termination of the plateau period on the corresponding thermal history curve. On this basis, Figs. 5, 6a and 7 reveal the existence of a non-zero temperature gradient ahead of the dendritic solidification front. The gradient may be sensitive to the casting conditions and, consequently, to the variations in ingot macrostructure, but this has not been measured in the present work. Apparently, this gradient does not exceed 0.05° C mm^{-1} and persists until the front reaches the centreline of the casting. Moreover, Figs. 5, 6a and 7 also indicate that the maximum plateau temperature that has been measured by any of the thermocouples increases with its distance from the mould surface. Therefore, it is concluded that in experiments of this kind the temperature of the solidification front increases continually as the front advances towards the centreline of the casting, as schematically illustrated in Fig. 8a. In fact this seems a more realistic picture of dendritic solidification in ingot castings than the hypothesis of constant dendritic growth temperature suggested in the past [7, 8] especially when purely columnar dendritic growth is concerned. Evidence in support of this statement is that in ingot castings the distance solidified, x, is related to the freezing time, t, by an equation of the form [23]:

$$x = at^{1/2} - b$$

Then, the nominal growth velocity of the solidifi-

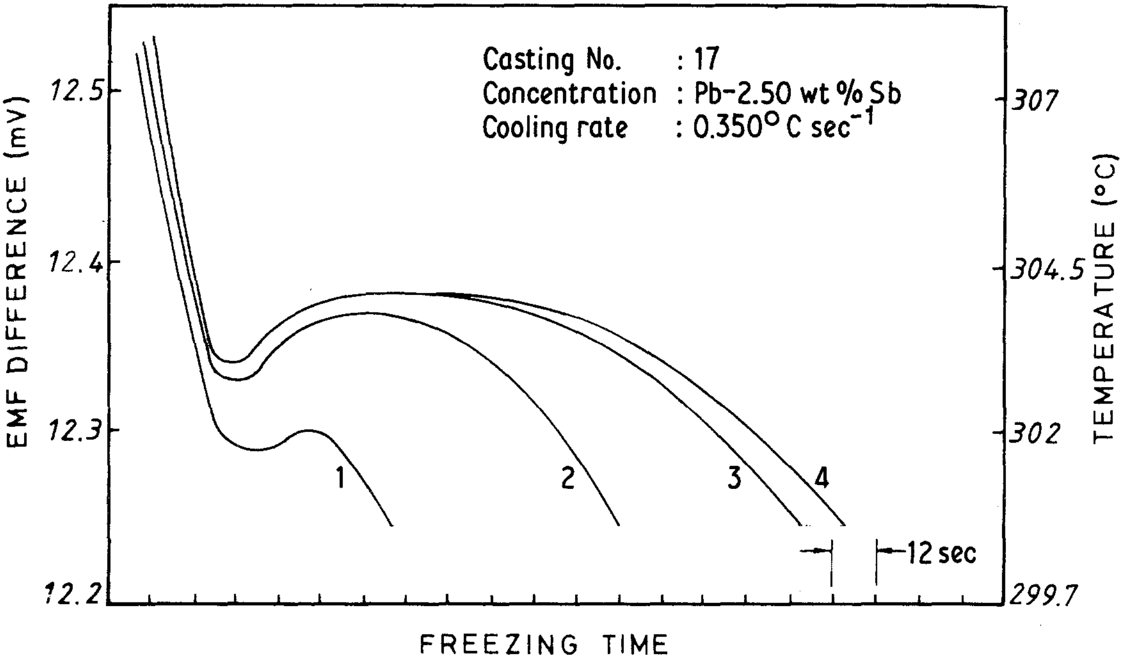

Figure 7 Thermal conditions existing during the dendritic growth stage of a fully equiaxed ingot.

cation front, v, is given by

$$v = \text{constant} \times t^{-1/2}$$

It follows that the velocity of the dendritic solidification front is expected to decrease with increasing distance from the mould wall surface, and, as Burden and Hunt estimate in unidirectional growth experiments [11], in columnar structured castings this is also expected to be accomplished with a definite rise in the tip temperature. It is also suggested that in experiments of this kind, provided that the resulting macrostructure is purely columnar, one should be able to derive distance solidified–solidification time, as well as nominal rate of advance of the columnar dendritic front–solidification time curves, as given in Figs. 8b and c, respectively, which can then be employed in estimating the equilibrium liquidus temperature of the alloy under consideration by simply extrapolating the data to zero growth velocities and finding the corresponding columnar dendrite tip temperature.

3.2. Effect of solute content upon grain structure

Two parameters were selected in order to control the grain macrostructures: cooling rate and solute content. The results have identified the latter as being more effective than the former within the range of the parameters employed. Furthermore, this part of the work has demonstrated a continuous variation in the extent of columnar zone with antimony content, in good agreement with the generally accepted relationship between ingot structure and solute content [24]. However, a contradiction seems to exist between this work and an earlier study where an anomalous relationship was measured between the volume fraction of equiaxed zone and the antimony concentration [25]. The search for the origin of this difference was not the aim of the work; however, the matter has subsequently been explored and established firmly [26] that over a range of casting conditions the relationship between the macrostructure and the antimony content in Pb–Sb ingot castings tend to obey the generally accepted trend.

3.3. Origin of equiaxed crystals

The *in situ* solidification technique does not allow the operation of the big-bang mechanism of equiaxed crystal formation. Therefore, the possible sources of equiaxed zone formation in ingot castings of this work could be either crystal fragments detached from the columnar or free surface dendrites or the nuclei forming ahead of the columnar front. In fact, comparison between the results obtained from castings of different grades of antimony additions can be revealing in under-

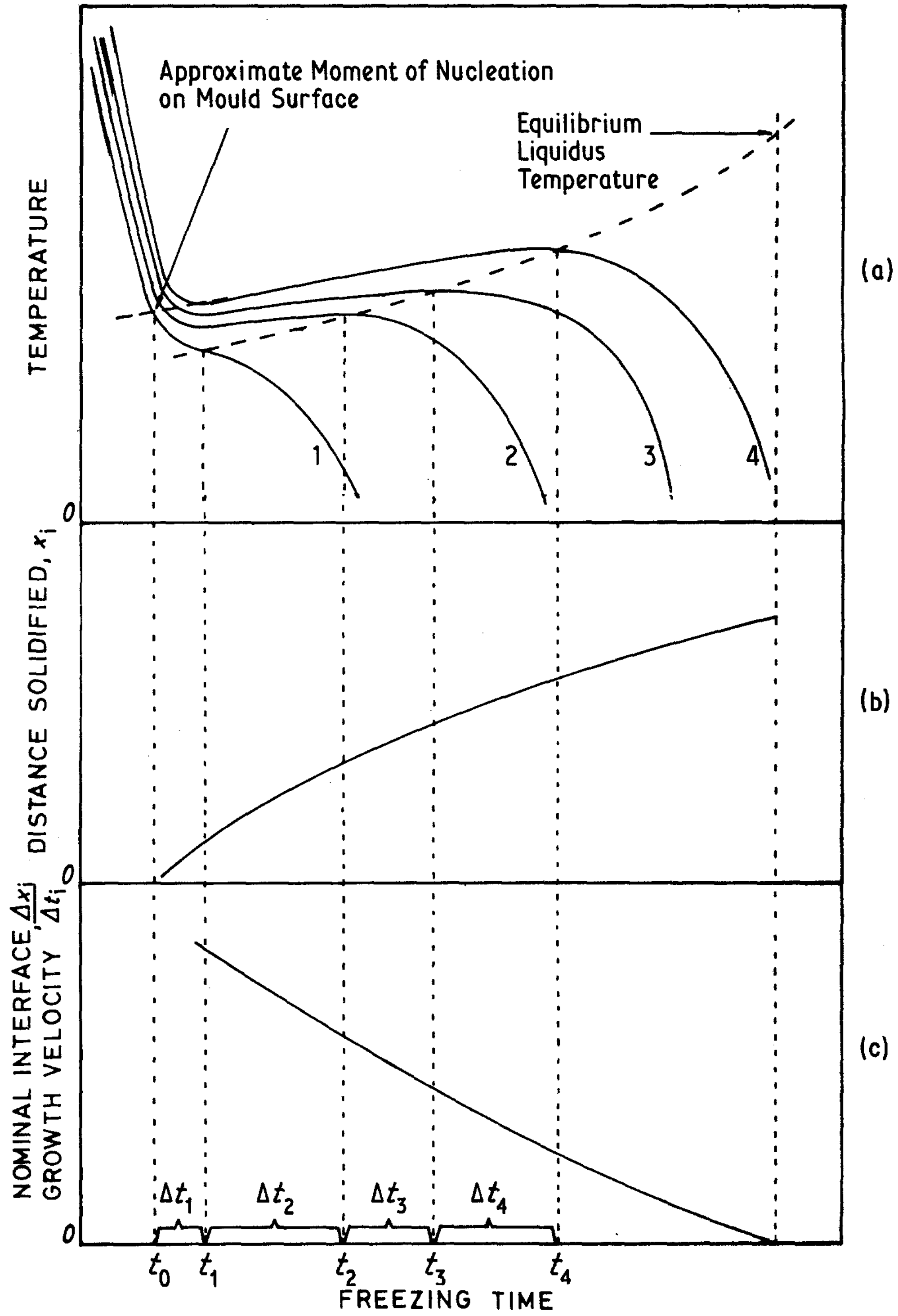

Figure 8 Hypothetical thermal analysis data for fully columnar dendritic solidification where the dotted line indicates the expected variation of the dendritic front temperature. (b), (c) Plots of distance solidified against time, and nominal growth velocity of columnar front against time, respectively. The figures also indicate the method of estimation of the equilibrium liquidus temperature of the alloy.

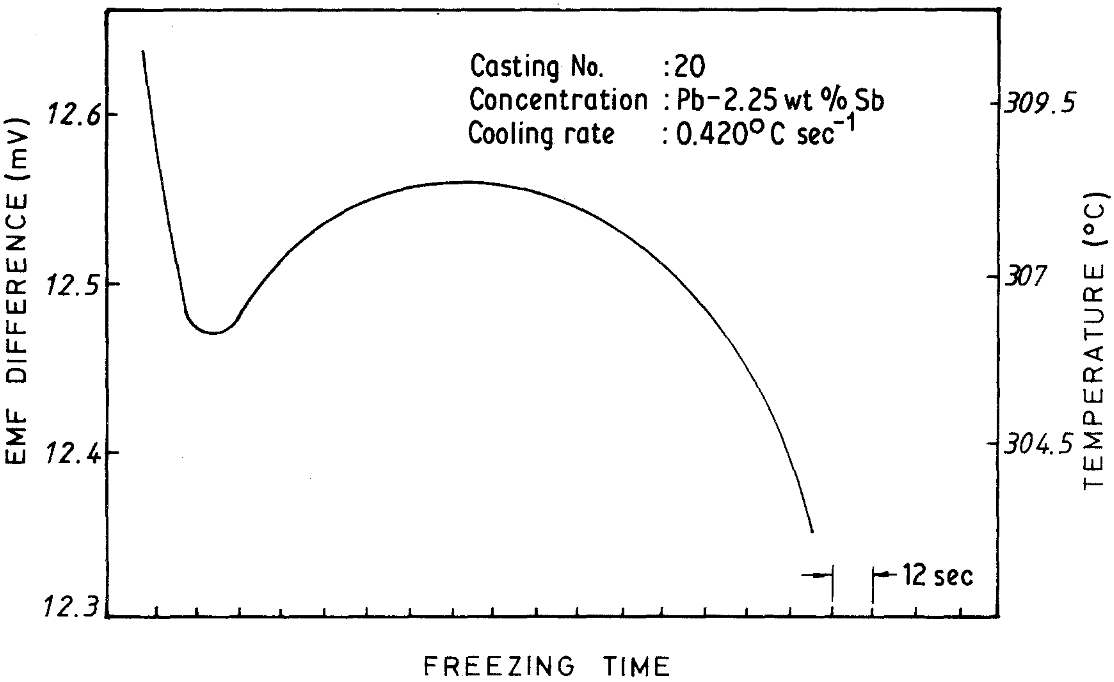

Figure 9 A thermal history curve obtained along the centreline of a columnar–equiaxed structured ingot.

standing the dominant mechanisms of equiaxed crystal formation in the castings of the present work. In a series of ingots where high purity antimony were dissolved in the alloy preparation, fully columnar structures have resulted at solute levels up to 5 wt% Sb, whereas the use of commercial grades of antimony displayed fully equiaxed ingot structures at solute levels as small as 2.5 wt% Sb. Thermal history curves measured on the centreline of castings of comparable compositions, say Pb–2 wt% Sb, one containing high purity and the other commercial grade antimony are presented in Figs. 4a and 9, respectively. From these figures, dendritic growth appears to have occurred at a faster rate in the fully equiaxed ingot than in the fully columnar one as would be expected and also that the purity level of antimony used could have no major influence upon either the initial thermal undercooling or the maximum plateau temperatures on the thermal history curves. Obviously, the dendrite detachment mechanisms of Jackson *et al.* [5] and O'Hara and Tiller [6] or the dendrite showering mechanism of Southin [7] could not be the sole sources of equiaxed crystal formation, since these mechanisms would have equal opportunities to operate irrespective of the purity level of antimony used. Accordingly, the constitutional supercooling hypothesis of Winegard and Chalmers [3] seems to deserve greater attention as a highly active source of equiaxed zone formation in ingot castings than it has ever had.

Direct observation studies have also identified another possible source of equiaxed crystal formation that has not previously been reported in the literature whereby the crystal bits transformed into the bulk liquid through interdendritic fluid flow. Obviously, the extent to which this mechanism can be effective in metal castings should also depend upon the centreline freezing resistance of the castings that is known to increase with solute content and cooling rate [27], which are recognized to have direct relevance to the extent of equiaxed zone in ingot castings.

3.4. Growth of equiaxed crystals

When a set of thermal history curves corresponding to a columnar–equiaxed casting, such as that presented in Fig. 6a, is considered, there exists apparent recalescence events in the cooling curves belonging to locations that eventually remained in the equiaxed portion of the ingot, as shown in Fig. 6b. On this basis, it is suggested safely that recalescence is the result of the release of latent heat from equiaxed dendritic growth. Also, initiation of thermal recalescence in the volume of the melt surrounding an interior thermocouple, say thermocouple number 4 in this case, is accompanied by the passage of the dendritic solidifi-

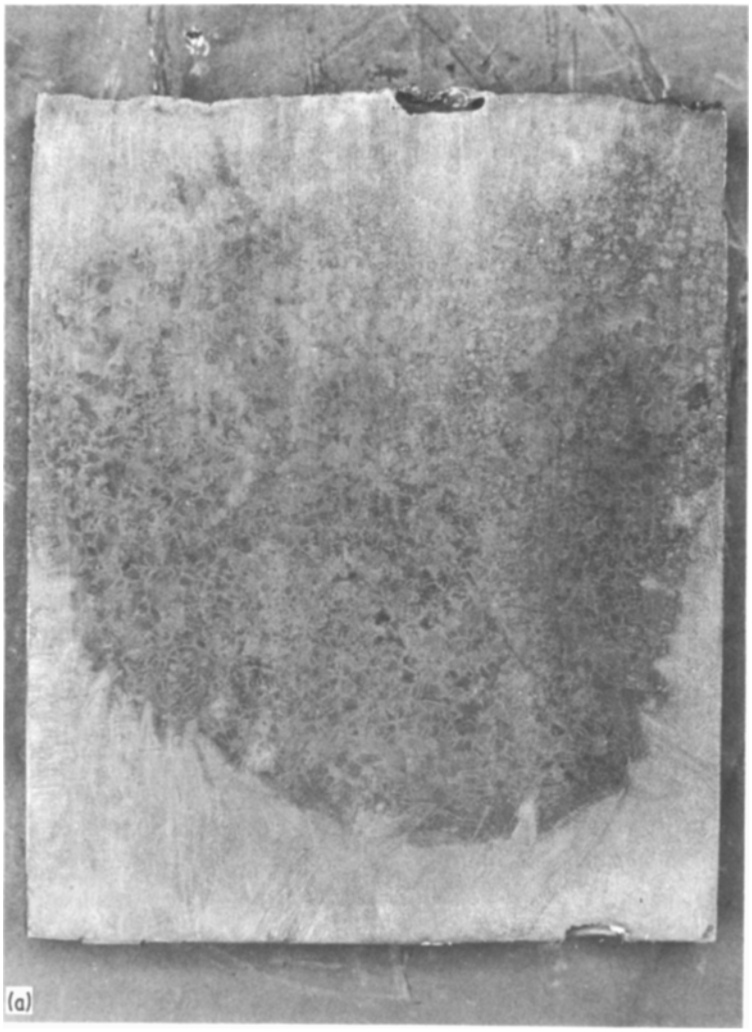

Figure 10 (a) Interrupted solidification structure of the central portion of a three-part casting. (b) Schematic illustration of the thermal conditions at an early stage of solidification process ending with a columnar–equiaxed structure. (c) Equiaxed dendritic growth ahead of a columnar dendritic front. (d) Illustration of the process of attachment of equiaxed dendrites to the columnar interface towards the bottom zone of the casting. (e) Schematic illustration of the thermal conditions at a later stage of the solidification process.

cation front by the thermocouple 2. However, the final ingot structure demonstrates that columnar equiaxed transition occurred at a location well beyond this point. These observations permit two major deductions to be made: (i) commencement of equiaxed dendritic growth ahead of the columnar front cannot immediately halt columnar growth but both type of crystals grow simultaneously at least for a finite period of time; and (ii) equiaxed dendrites grow at a higher temperature than columnar ones. A similar argument equally applies to fully equiaxed castings. Accordingly, as Fig. 7 illustrates, within a single casting, equiaxed dendritic growth temperature increases with distance from the mould surface towards the centreline of the ingot and also that there is no constant equiaxed dendritic growth temperature but that these crystals grow with increasing temperature until their growth terminates.

3.5. Columnar–equiaxed transition

A mechanism of CET, based upon the direct observation studies in combination with the results of thermal analysis work conducted on metallic ingot castings, is suggested below. This proposal mainly applies to *in situ* solidification processes. It may also apply to poured castings provided that high superheats are employed so that steep thermal gradients exist in the bulk liquid until solidification begins.

Solidification is suggested to begin on the bottom surface of the mould irrespective of the casting practice employed. This point has been observed on both cyclohexanol–phenol red castings and also demonstrated on the solidification structure obtained by quenching the central portion of a three-parts ingot casting (Fig. 10a), which normally solidifies with a coarse columnar–coarse equiaxed structure. Thereafter, the solid

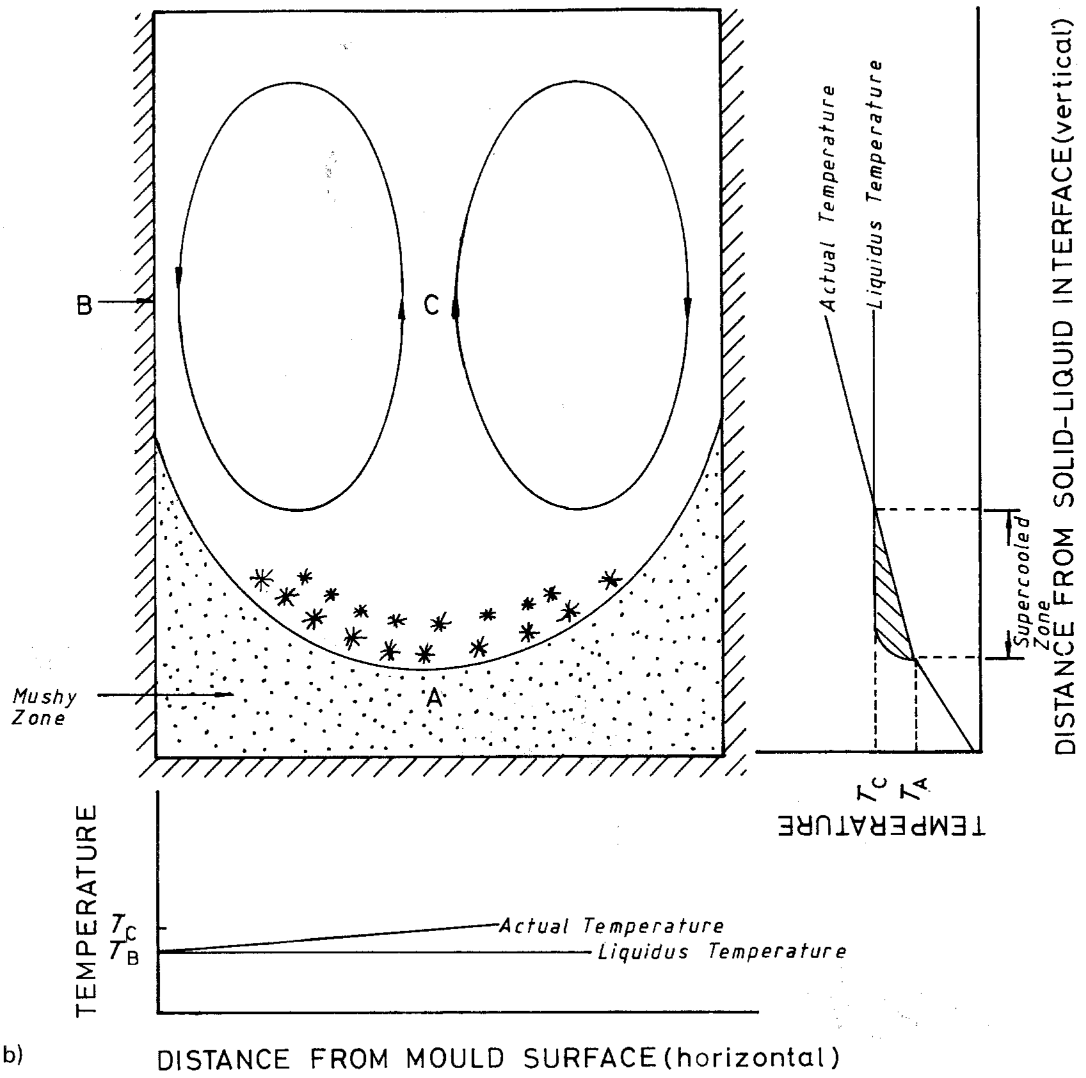

Figure 10 Continued.

skin formation spreads upwards, covering the whole surface of the mould. Equiaxed crystals first appear in the bottom zone of the ingot as clearly demonstrated in Fig. 10a and then block the vertical columnar growth. Axial and radial temperature gradients in the casting at this stage are schematically illustrated in Fig. 10b. It is proposed that while a constitutionally supercooled layer of liquid has developed at the bottom zone, conditions still do not permit solidification to begin on the side walls of the mould. As solidification proceeds, a continuously supercooled layer develops ahead of the horizontally growing columnar interface, the maximum supercooling being at some distance from the interface. Now, equiaxed crystals appear in front of the interface at a location where supercooling reaches its maximum. This proposal is based upon the observations made during solidification of the cyclohexanol–phenol red system, as presented in Fig. 10c. It is also in agreement with the analytical work of Witzke *et al.* [17] who have demonstrated that constitutional supercooling may exist and passes through a maximum within the thermal boundary layer ahead of the columnar front. However, formation of equiaxed crystals in this fashion cannot block columnar growth immediately, instead, they tend to follow the bulk liquid convection pattern. The probable reason given for this is that the crystals are attached to the outermost layer of the bulk liquid convection where the flow velocity is at its maximum and also that drag exerted by the flow

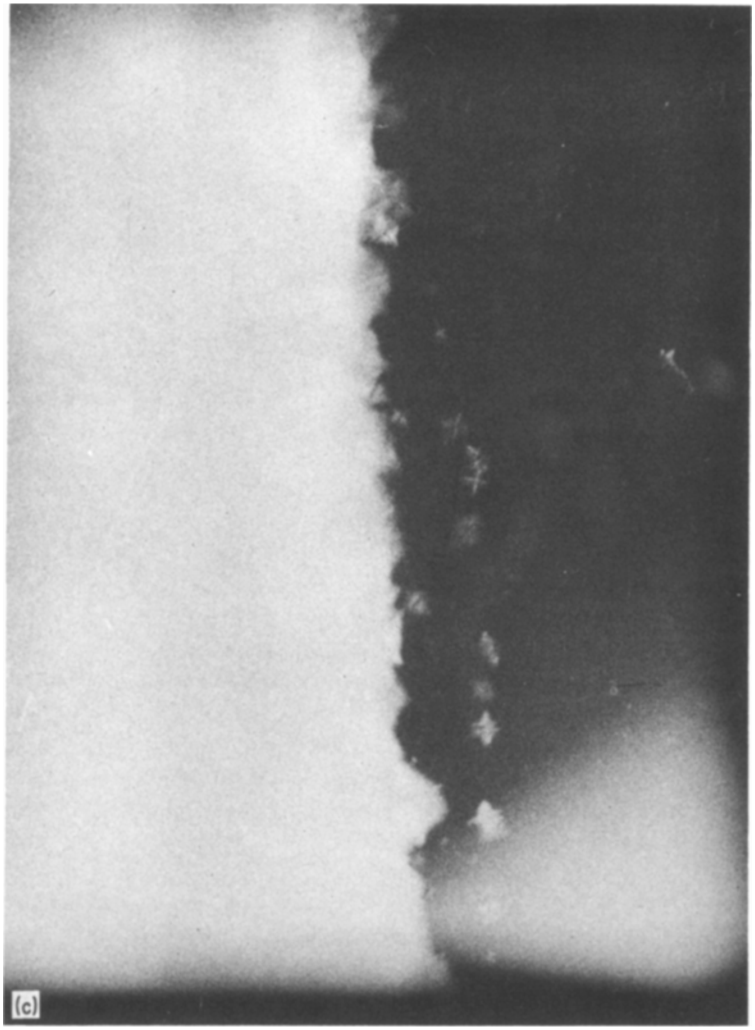

Figure 10 Continued.

dominates over the gravitational acceleration. More towards the bottom zone of the casting, some of these equiaxed crystals may be attached to the columnar interface, as can be observed in Fig. 10d, whereas most of them continue their motion with tendencies either to settle freely or to develop a central column of equiaxed crystals. These crystals are then expected to multiply intensively in this region of the ingot, because they have formed at a lower temperature and are now in contact with a hotter liquid. When the crystals in this central zone of the casting grow to sufficiently large sizes, gravitational acceleration is expected to dominate and they would quit the flow to settle freely upon those already settled.

However, it is suggested that diffusion fields surrounding these crystals will solute-enrich the outer layer of the flow and this, in turn, reduces the equilibrium liquidus temperature of the thermal boundary layer ahead of the columnar front. In the meantime, the columnar interface temperature would be expected to increase and the part of pouring superheat would have reduced, both processes leading to a reduced thermal gradient ahead of the interface. Consequently, (i) the extent of constitutional supercooling ahead of the columnar dendritic front decreases, showing down the columnar front, and (ii) the location in the casting where constitutional supercooling reaches a maximum shifts more towards the centreline of the ingot, removing the layer of equiaxed crystal formation away from the columnar interface. These conditions are illustrated in Fig. 10e. It is anticipated that all these processes will occur continuously until finally the columnar growth nearly terminates and also that the con-

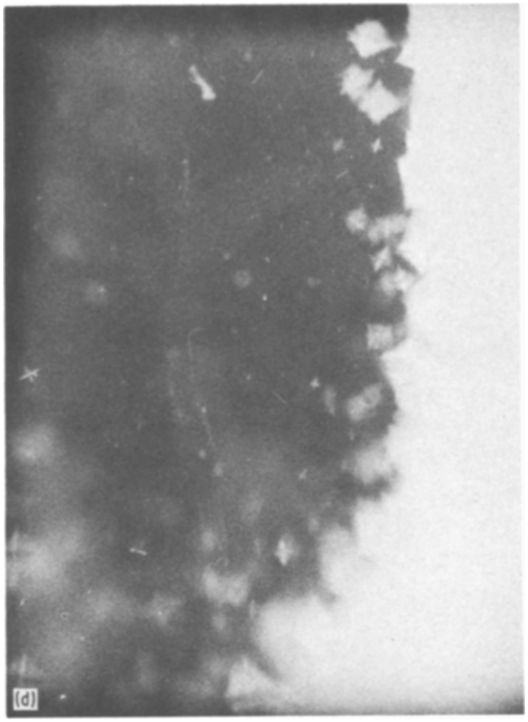

Figure 10 Continued.

stitutionally supercooled zone spreads throughout the interior liquid.

In ingots solidifying in the manner described above, a short columnar zone or a peripheral layer of larger equiaxed grains should always exist before the normal equiaxed zone, and also the extent of the columnar zone should increase with distance from the bottom surface of the ingot. In fact, these are generally the cases in laboratory- and industrial-scale castings.

Depending upon the casting conditions, dendrite branches dislodged from the free surface of the ingot may also be an effective source of equiaxed zone formation. Initially, when the bulk liquid convection is severe, branches that are dislodged from the surface would join the outer layer of the flow and then disintegrate into smaller pieces as a result of the shear couple resulting from the differences in the flow velocities between adjacent layers of the flow. The sequence of events that may occur thereafter is expected to be similar to those described in the previous case. However, when the flow diminishes the showering of dendrite pieces and branches from the upper surface dendrites, as Southin [7] proposed, would be the dominant mechanism of the formation of equiaxed crystals.

4. Conclusions

As a result of thermal analysis of laboratory-scale ingot castings of the Pb–Sb alloy system under the conditions described above, and the observations made during solidification of cyclohexanol–phenol red castings, the following conclusions were arrived at.

1. Regardless of the resulting macrostructure, a dendritic skeleton of castings develops with some undercooling at dendritic tips and also with a slight but positive temperature gradient, not exceeding 0.05° C mm^{-1} in the liquid ahead of the dendritic solidification front. Undercooling at the dendritic solidification front decreases with increasing distance from the mould wall surface.

2. The dendritic skeleton develops at a faster rate at higher cooling rates and solute contents.

3. In castings leading to a columnar–equiaxed structure, formation of equiaxed crystals ahead of the columnar dendritic interface can not immediately block columnar growth, but both types of crystal grow simultaneously for a definite period of time, equiaxed crystals growing at a higher temperature than the columnar ones.

4. The dependence of columnar zone length in Pb–Sb castings upon the antimony content does obey the generally accepted trend between the ingot structure and the solute content.

5. Heterogeneous nucleation in the liquid ahead of the columnar front at some stage of the solidification process has been proposed as a dominant mechanism of equiaxed crystal formation.

6. A novel picture of CET, that has been based upon the observations made in this work, points out the important role of bulk liquid convection on the mechanism of CET.

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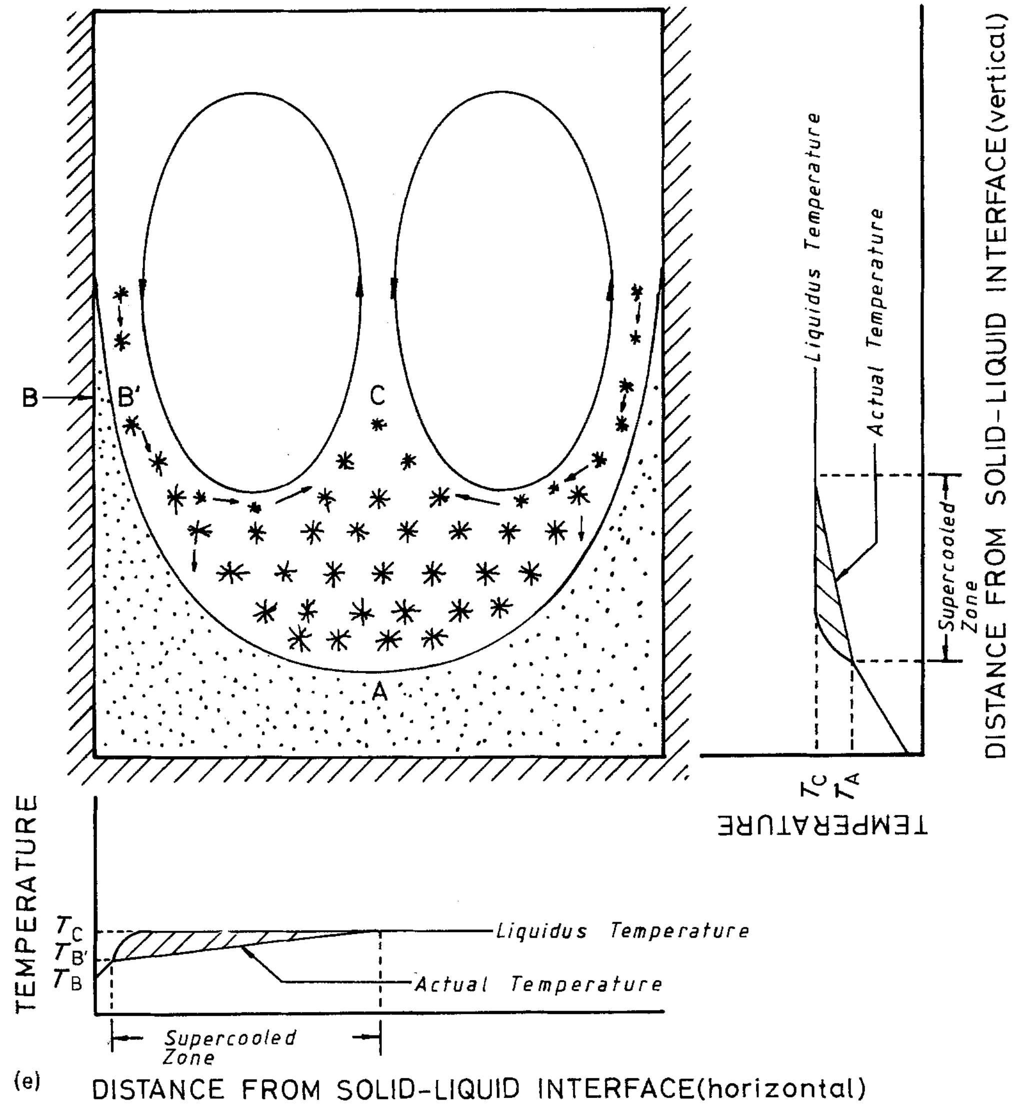

Figure 10 Continued.

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