JOURNAL OF MATERIALS SCIENCE 32 (1997) 1239–1248

Influence of the process parameters on the volume change during the eutectic reaction of S.G. cast iron: a computer simulation

QIMING CHEN
Materials Research Institute, Sheffield Hallam University, City Campus Pond Street, S1 1WB, Sheffield, UK

E. W. LANGER*, P. N. HANSEN‡
** Metallurgy and ‡Thermal Processing of Materials, PI Technical University of Denmark, 2800 Lyngby, Denmark*

In earlier research work, a model of volume change during the solidification of S.G. iron was proposed and the effect of the eutectic growth was discussed in detail. With the proposed model some calculations have been made to simulate the volume change and the influence of process parameters, such as inoculation, pouring temperature, heat transfer coefficient and section size of casting on the volume change during the solidification of S.G. cast iron in the present paper. The same trends as known from foundry practice can be seen qualitatively and quantitatively.

1. Introduction

Understanding of the shrinkage behaviour of S.G. iron is very important for the purpose of making a defect-free casting in foundry practice. However due to the graphitization expansion and the contraction with cooling during solidification, the shrinkage behaviour of S.G. iron is very complex. It seems that the key point to understanding the shrinkage behaviour of S.G. iron is to describe the volume change kinetics and its effect as well as the mass flow during the evolution of microstructure or the eutectic reaction as a whole process. The first thing that should be done is to set up a volume change model. Furthermore the graphitization expansion results from the eutectic growth kinetics with two phases of graphite and austenite. Hence it is reasonable to discuss the volume change during solidification with the nucleation and growth law of the eutectic reaction. In earlier research works [1, 2] the volume change model was proposed and discussed in detail. The results show that it is feasible to couple the volume change model with the eutectic growth kinetic model to describe the volume change kinetic process.

The volume change during the eutectic solidification is sensitive to the process parameters [3, 4]. In this paper, several calculations have been performed with the volume change kinetic model described in [1, 2]. The purpose of this study is to simulate the influence of the process parameters on the volume change during the eutectic solidification. It is assumed that there are no other phases formed except graphite and austenite for a given alloy with eutectic composition and for a given kind of sand mould.

2. Simulation of the influence of the effectiveness of inoculation on the solidification of S.G. cast iron and the volume change during the solidification of S.G. cast iron

2.1. Influence of the effectiveness of inoculation on nucleation

According to the previous experimental work by Lacaze and co-workers [5, 6] the effectiveness of inoculation can be expressed by the nucleation constant A. In this simulation a large value and a small value of the nucleation constant are used to characterize the effectiveness of the inoculation of the melts.

The distributions of the increment of the number of nuclei along the radius of a cylindrical casting for both cases are shown in Fig. 1 and the total number of nuclei is shown in Fig. 2.

As shown in Fig. 3, the difference between the two cases is obvious. For a given time and for the case of the strong inoculation the radius of the eutectic cells is quite different along the radius of the cylindrical casting. But for the case of the weak inoculation the difference is the radius of the eutectic cell is small along the radius of the casting. This confirms that for the strong inoculation the controlling factor is the nucleation rate but for weak inoculation the controlling factor of eutectic reaction is the growth rate, if the conditions of heat transfer are the same.

2.2. Influence of the effectiveness of inoculation on the undercooling

The influence of the effectiveness of inoculation on the undercooling are shown in Fig. 4 for comparison.

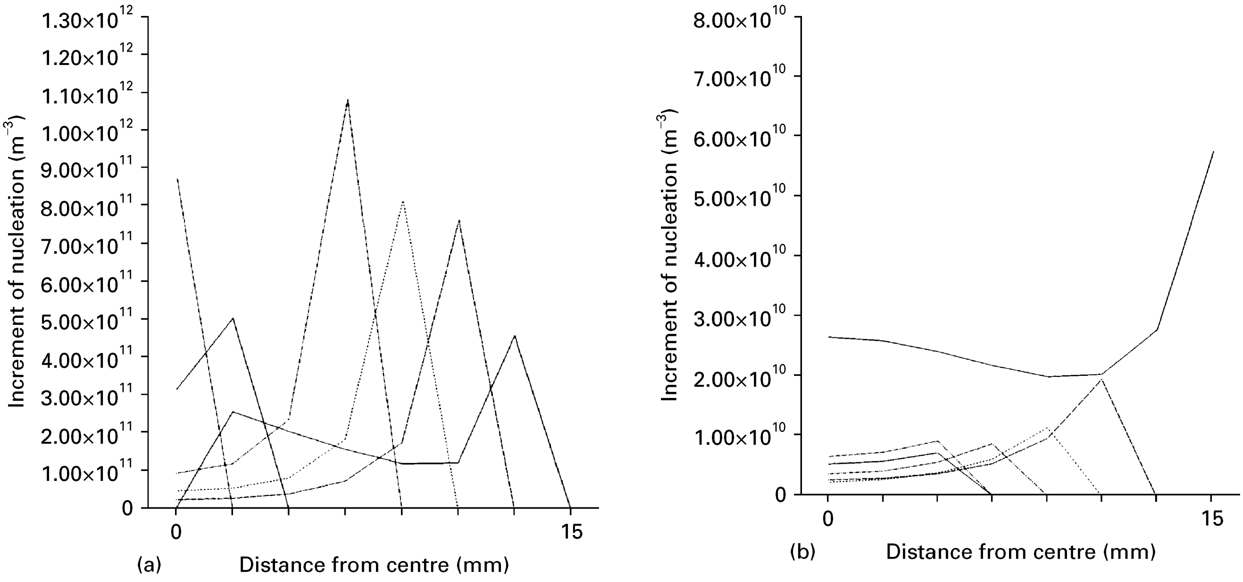

Figure 1 Distribution of the increment of nuclei on the radius of casting for (a) strongly inoculated ($A = 40 \times 10^{11}$) and (b) weakly inoculated ($A = 1 \times 10^{11}$) melts, respectively. Key: (a) —— 46 s; – – – 66 s; · · · · 86 s; – · – · – 106 s; —— 126 s; – · · – · · – 146 s; (b) —— 41 s; – – – 51 s; – · – · – 56 s; – · – · – 61 s; —— 66 s; – · · – · · – 71 s.

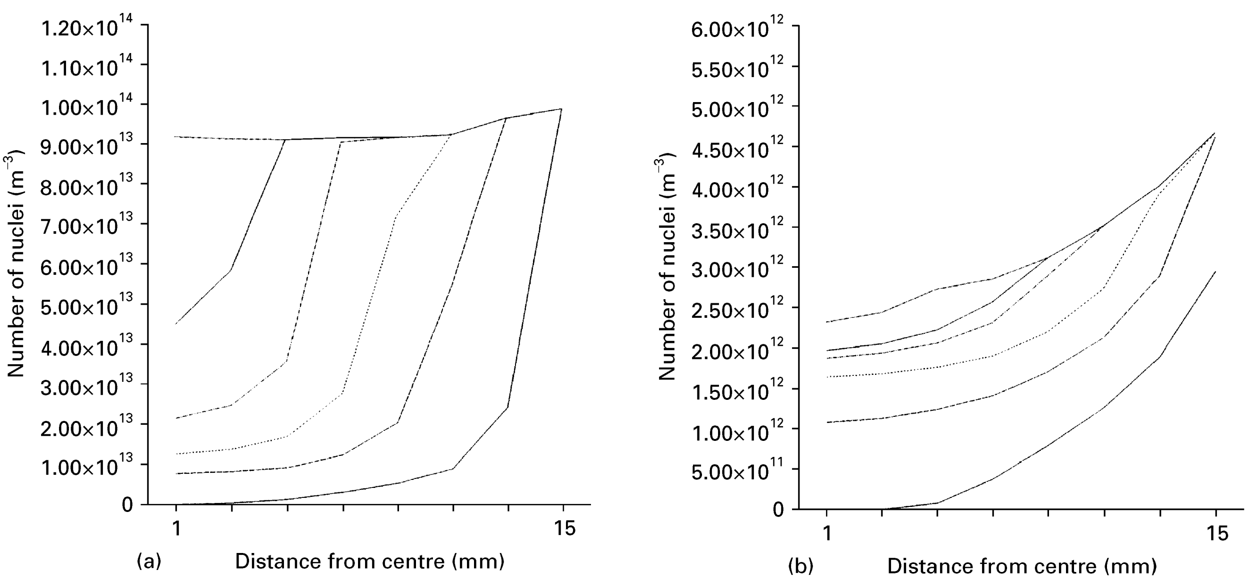

Figure 2 Nucleation number along the cylindrical casting for two values of nucleation constant. (a) $A = 40 \times 10^{11}$. (Key: —— 46 s; – – – 66 s; · · · · 86 s; – · – · – 106 s; —— 126 s; – · · – · · – 146 s.) (b) $A = 1 \times 10^{11}$. (Key: —— 36 s; – – – 41 s; · · · · 46 s; – · – · – 56 s; —— 61 s; – · · – · · – 71 s.)

Firstly, for a strongly inoculated melt the undercooling is smaller than that in a weakly inoculated melt. Furthermore it is evident that the distribution of undercooling along the radius of casting is quite different between the strongly inoculated melt (Fig. 4a) and weakly inoculated melt (Fig. 4b). For the strongly inoculated melt the undercooling occurs in a very narrow range or only occurs in the solidification front and goes on from surface to centre along the radius of casting with the progress of the solid front, keeping the undercooling almost constant. However for weak inoculation the undercooling occurs in a relative large area evenly throughout the section of casting and the value of undercooling increases with the progress of solidification. The value of undercooling depends on the controlling factor of the eutectic reaction. If the controlling factor is nucleation the undercooling will be small because the onset of the nucleation at the front of solidification results in a fast solidification rate (a great amount of nuclei grow at the same time) and relatively small size of the eutectic cell as seen in Fig. 3. But for weak inoculation the growth rate is the controlling factor since the number of nuclei is relatively small. The eutectic cell must grow a relatively large size. This is why fading inoculation is always accompanied with a large undercooling and the formation of cementite during the solidification of S.G. cast iron.

2.3. Influence of the effectiveness of inoculation on the solid fraction

As shown in Fig. 5, for the strong inoculation the change of the solid fraction occurs in a very narrow

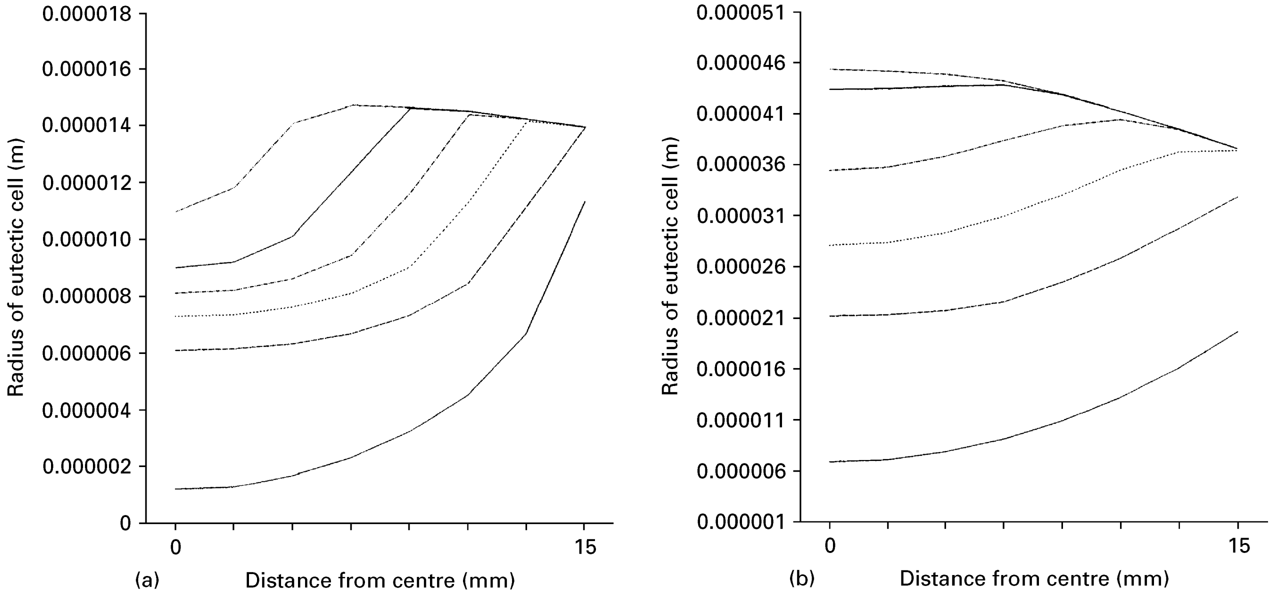

Figure 3 Radius of eutectic cell along the cylindrical casting. (a) $A = 40 \times 10^{11}$ (Key: —— 46 s; – – – 66 s; · · · · · 86 s; – · – · – 106 s; —— 126 s; – · · – · · – 146 s). (b) $A = 1 \times 10^{11}$ (Key: —— 41 s; – – – 66 s; · · · · 101 s; – · – · – 131 s; —— 161 s; – · · – · · – 170 s).

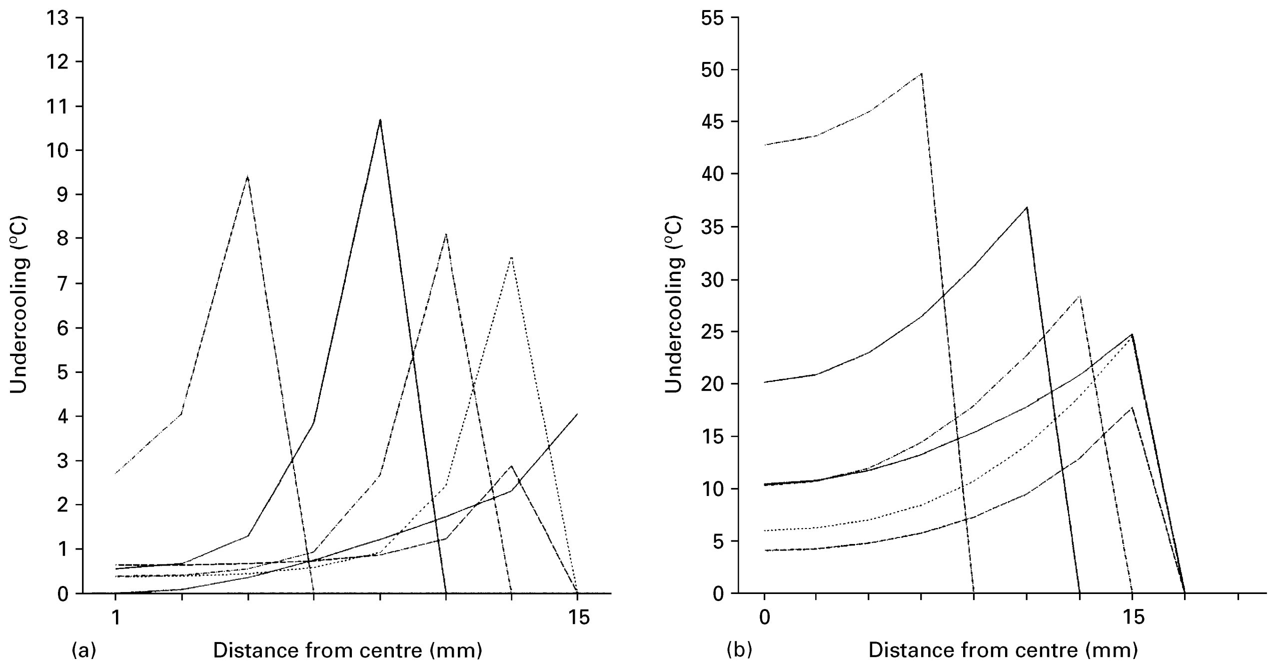

Figure 4 Effect of inoculation on the undercooling along the radius of casting. (a) $A = 40 \times 10^{11}$ (Key: —— 46 s; – – – 66 s; · · · · · 86 s; – · – · – 106 s; —— 126 s; – · · – · · – 146 s). (b) $A = 1 \times 10^{11}$ (Key: —— 41 s; – – – 81 s; · · · · 101 s; – · – · – 121 s; —— 141 s; – · · – · · – 161 s).

range along the radius. It means that the mushy zone is relatively narrow near the solidification front. This situation proceeds until the end of the eutectic reaction. For the case of weak inoculation, the curves for solid fraction with time are more inclined than those for strong inoculation. In this situation the growth of the eutectic cells occurs throughout the section of the casting. Finally they reach the same value of solid fraction and this means the eutectic reaction proceeds throughout the casting. So it is very difficult in this situation to form a hard skin which can resist the effect of expansion at the early stage of the eutectic reaction.

2.4. Influence of the effectiveness of inoculation on the volume changes

The volume changes are shown in Fig. 6 and the corresponding density distribution is shown in Fig. 7. The curves for the strong inoculation is much steeper than those for the weak inoculation because the mushy zone is narrow and the eutectic reaction controlled by the nucleation rate.

The comparison between the volume changes of the two cases is shown in Fig. 8 with the cooling curves. The difference in the volume changes of casting results from the difference in the eutectic temperatures between the two cases. This can be seen in Fig. 8a. For

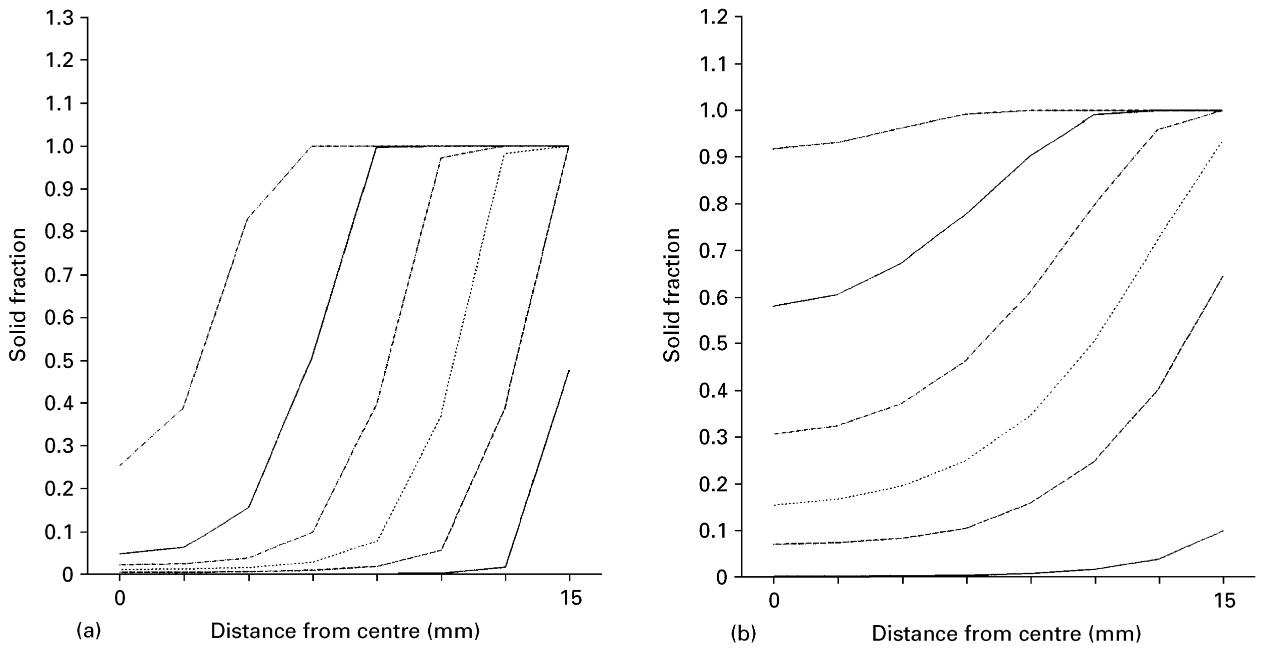

Figure 5 Influence of the effectiveness of inoculation on the solid fraction. (a) $A = 40 \times 10^{11}$ (Key: —— 46 s; – – – 66 s; · · · · · 86 s; – · – · – 106 s; —— 126 s; – · · – · · – 146 s). (b) $A = 1 \times 10^{11}$ (Key: —— 41 s; – – – 66 s; · · · · 91 s; – · – · – 116 s; —— 126 s; – · · – · · – 146 s).

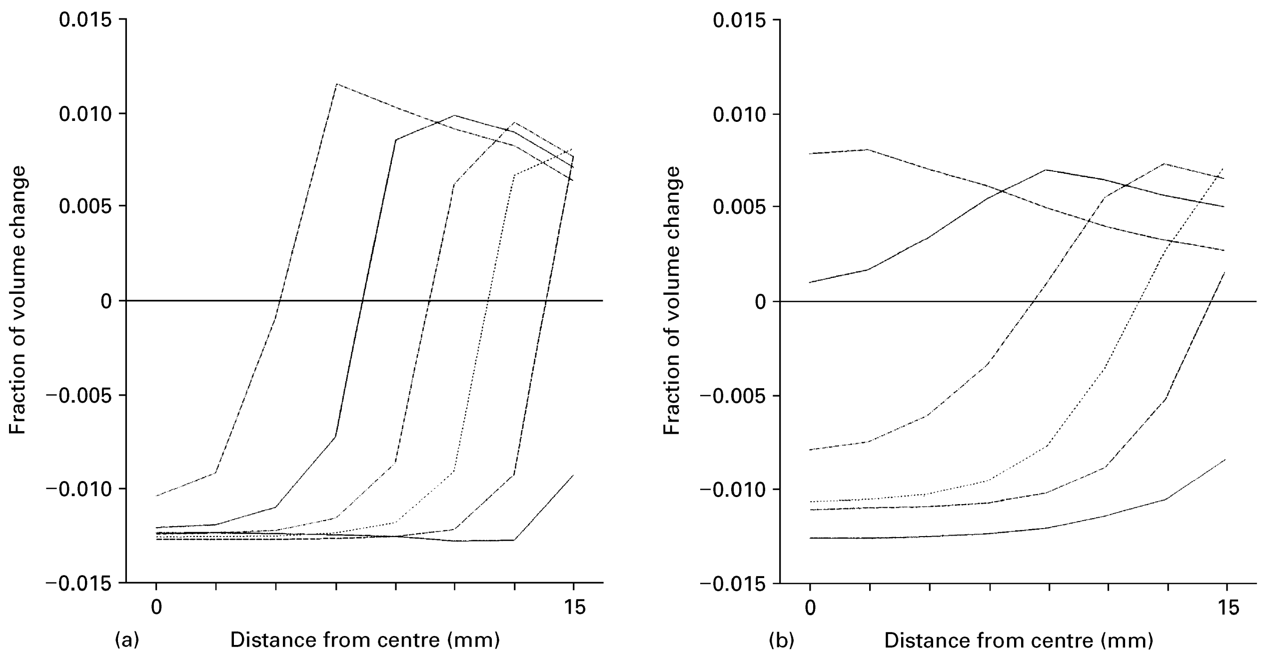

Figure 6 Influence of the effectiveness of inoculation on the volume change fraction along the cylindrical casting. (a) $A = 40 \times 10^{11}$ (Key: —— 40 s; – – – 60 s; · · · · · 80 s; – · – · – 100 s; —— 120 s; – · · – · · – 140 s). (b) $A = 1 \times 10^{11}$ (Key: —— 40 s; – – – 60 s; · · · · 80 s; – · – · – 100 s; —— 120 s; – · · – · · – 140 s).

weak inoculation the volume of the mushy zone is larger than that for strong inoculation. Therefore the volume change of the mushy zone for a given time for weak inoculation is much more than that for the strong inoculation and so is the corresponding effect on the mould wall which results in the dilatation of the mould cavity.

2.5. Influence of the effectiveness of inoculation on R_A/R_G

When the Rappaz's growth kinetics are employed, R_A/R_G (R_A: radius of austerite, R_G: radius of graphite will change during the eutectic reaction since the change of carbon content in the residual liquid results in the increase of the growth rate of the austenite shell which is determined by the mass balance and the solute balance of the whole eutectic domain (see [2]). The influence of the effectiveness of inoculation on R_A/R_G is shown in Fig. 9.

Consequently, one can conclude that the influence of the effectiveness of inoculation on the volume change during the eutectic reaction of S.G. cast iron can be divided into two parts. Firstly, due to the effect of inoculation the volume of the effective mush zone (the mushy zone where $f_s > 0.1$) decreases and this

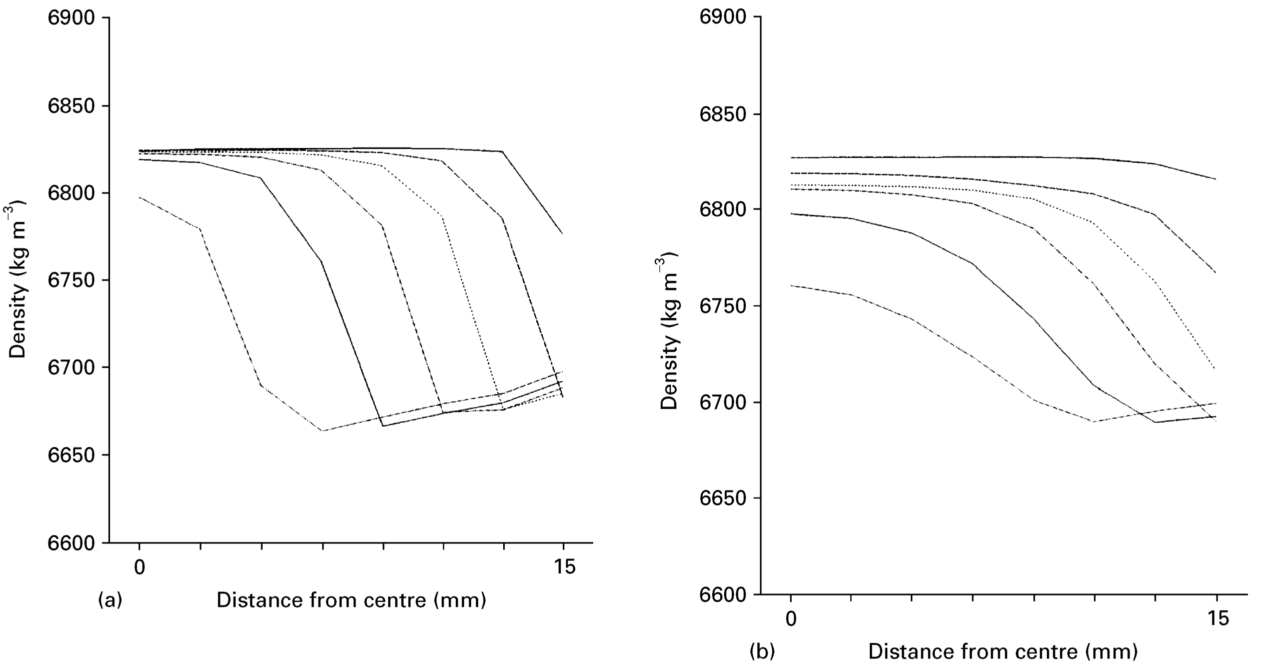

Figure 7 Influence of the effectiveness of inoculation on the density of mixture of the eutectic along the cylindrical casting. (a) $A = 40 \times 10^{11}$ (Key: —— 45 s; – – – 65 s; · · · · · 85 s; – · – · – 105 s; —— 125 s; – · · · – · · · – 145 s). (b) $A = 1 \times 10^{11}$ (Key: —— 40 s; – – – 60 s; · · · · 80 s; – · – · – 100 s; —— 120 s; – · · · – · · · – 140 s).

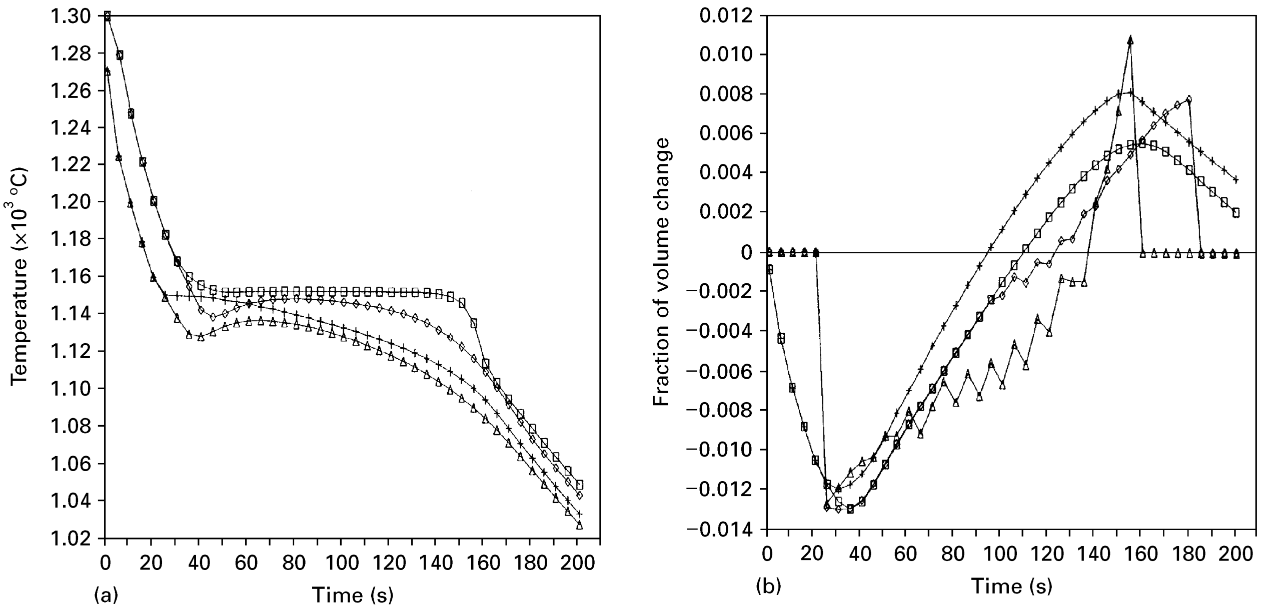

Figure 8 Comparison of the volume changes of casting due to the effectiveness of inoculation. (a) *C* means centre element and *S* means surface element; (b) *C* means casting and *M* means mushy zone. Keys (a) □ C, $A = 40 \times E10^{11}$; + S, $A = 40 \times 10^{11}$, ◇ C, $A = 1 \times 10^{11}$, △ S, $A = 40 \times 10^{11}$; (b) □ C, $A = 1 \times 10^{11}$; + C, $A = 40 \times 10^{11}$; ◇ M, $A = 1 \times 10^{11}$; △ M, $A = 40 \times 10^{11}$.

results in a decrease in the volume change of the mushy zone. Secondly, due to the effect of inoculation the eutectic reaction occurs at a higher temperature, which results in a relative larger specific volume of the phases. So the expansion of the casting volume with the strong inoculation will be larger than that with the weak inoculation, which is shown in Fig. 10. As a result, the effect of the strong inoculation decreases the volume change of the mushy zone but increases the volume change of the casting for a given section size of casting if there are no other phases forming. Although the volume of change of the casting is larger for the strong inoculation, the solid shell which is formed at the early stage of the eutectic reaction will resist the expansion force which is very weak since the increase in the volume change in the mushy zone is small and can be released by contact with the liquid phase. Consequently, the tendency of forming porosity is very weak. This phenomenon has been confirmed by the previous experimental works [3, 4].

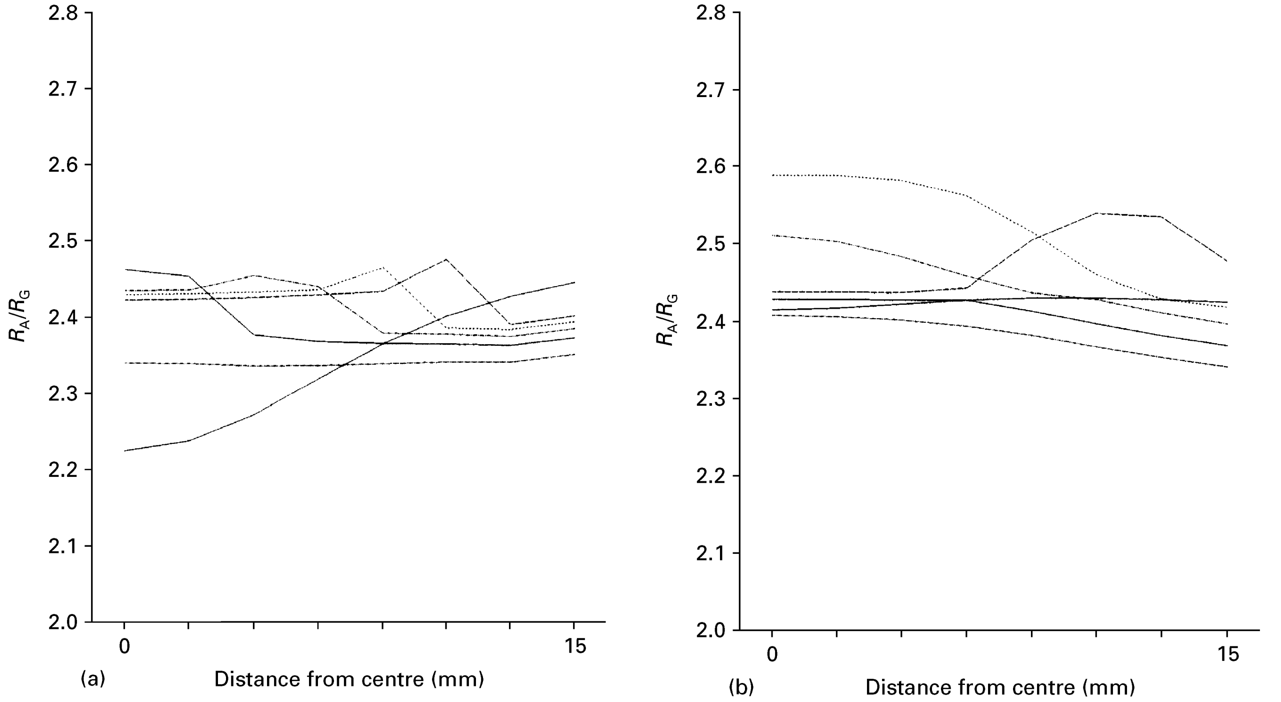

Figure 9 Influence of the effectiveness of inoculation on R_A/R_G (a) $A = 40 \times 10^{11}$ (Key: —— 51 s; – – – 86 s; · · · · · 116 s; – · – · – 146 s; —— 171 s; – · · – · · – 191 s). (b) $A = 1 \times 10^{11}$ (Key: —— 40 s; – – – 65 s; · · · · 115 s; – · – · – 145 s; —— 170 s; – · · – · · – 190 s).

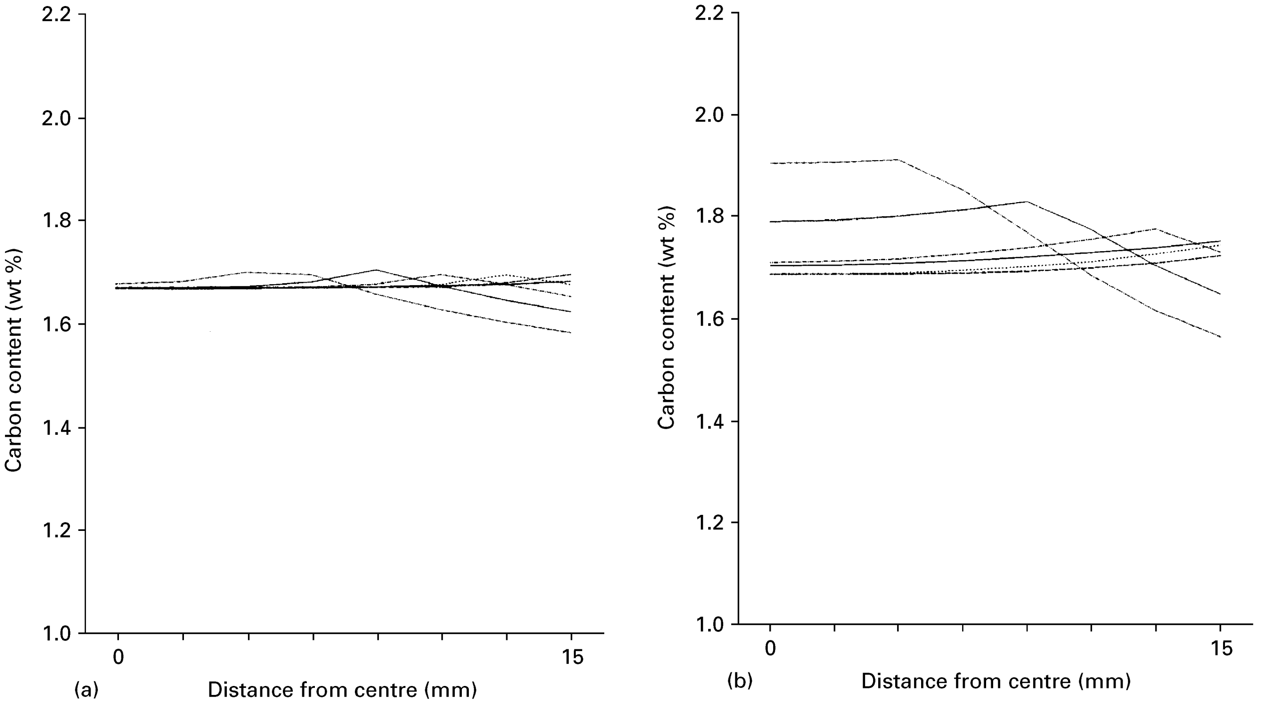

Figure 10 Influence of the effectiveness of inoculation on the changes of the carbon content of austenite during the eutectic reaction. (a) $A = 40 \times 10^{11}$ (Key: —— 45 s; – – – 65 s; · · · · · 85 s; – · – · – 105 s; —— 125 s; – · · – · · – 145 s). (b) $A = 1 \times 10^{11}$ (Key: —— 40 s; – – – 65 s; · · · · 96 s; – · – · – 120 s; —— 155 s; – · · – · · – 175 s).

3. Influence of pouring temperatures on the solidification and the volume change during the solidification

3.1. Influence of pouring temperature on the nucleation and growth of the eutectic cell (for the case of the linear nucleation law)

The influence of pouring temperature on the nucleation and growth of the eutectic cell with the linear nucleation law are shown in Figs 11, 12 and 13, respectively. For the case of a pouring temperature of 1350 °C, the nucleus number of the centre element is 2.9×10^{13} and that for the case of a pouring temperature of 1250 °C is 2.4×10^{13}. So the difference between the two cases can be omitted and it seems that the pouring temperature has no influence on the nucleation and growth of the eutectic cell if one assumes that the nucleation activity only depends on the thermal condition of the casting and the eutectic undercooling is independent of pouring temperature. But in

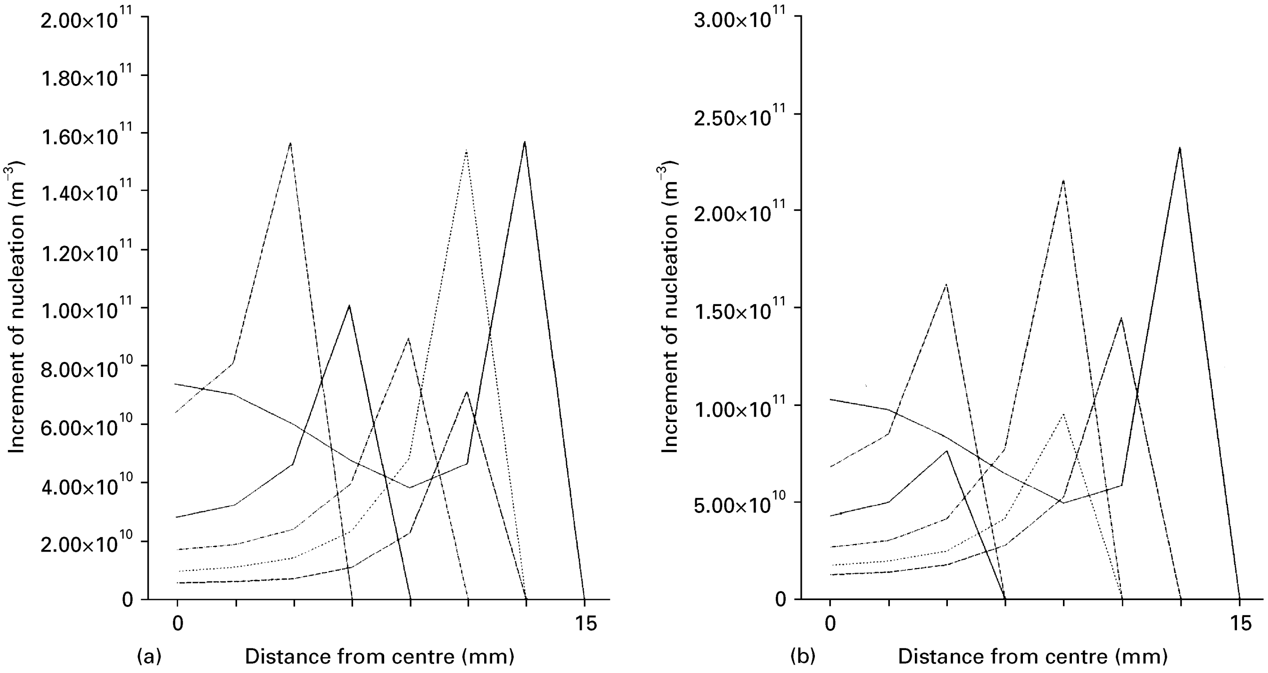

Figure 11 Influence of pouring temperature (TP) on the increment of nucleation, (a) $A = 10 \times 10^{11}$, TP = 135 °C (Key: —— 56 s; – – – 66 s; · · · · · 76 s; – · – · – 86 s; —— 106 s; – · · – · · – 126 s). (b) $A = 10 \times 10^{11}$, TP = 1250 °C (Key: —— 31 s; – – – 41 s; · · · · 51 s; – · – · – 61 s; —— 76 s; – · · – · · – 86 s).

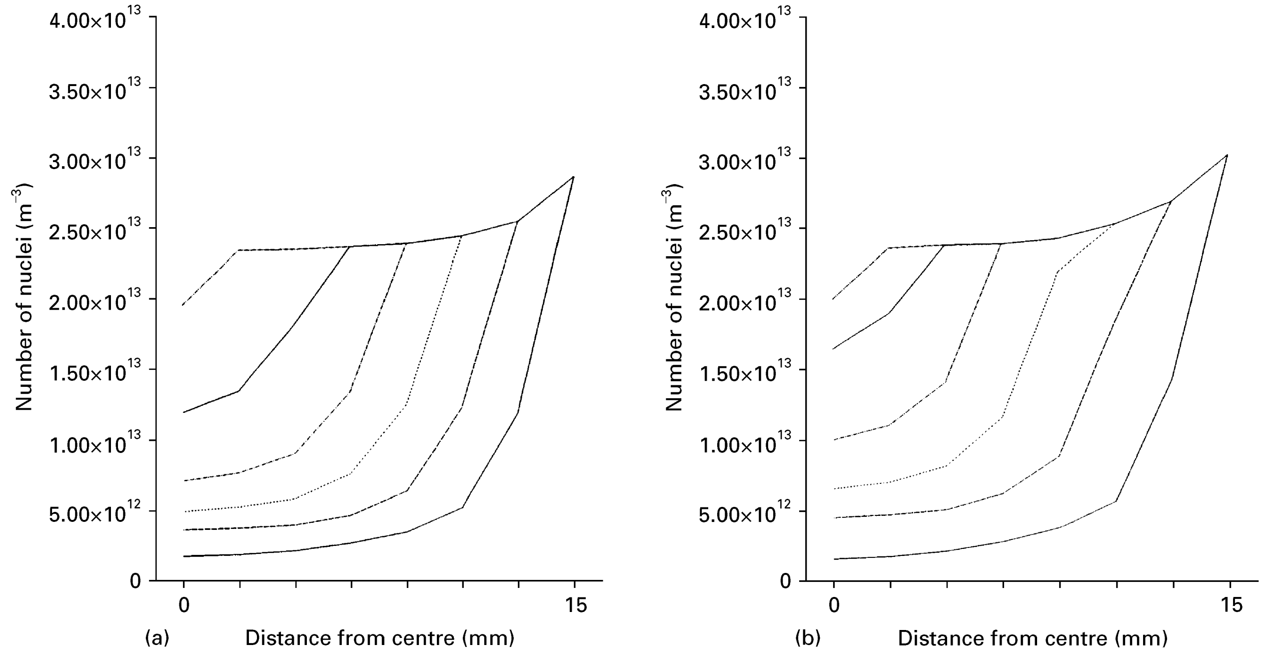

Figure 12 Influence of pouring temperature (TP) on the number of nucleation. (a) $A = 10 \times 10^{11}$, TP = 1350 °C (Key: —— 56 s; – – – 71 s; · · · · · 86 s; – · – · – 101 s; —— 121 s; – · · – · · – 136 s). (b) $A = 10 \times 10^{11}$, TP = 1250 °C (Key: —— 31 s; – – – 46 s; · · · · 61 s; – · – · – 76 s; —— 91 s; – · · – · · – 96 s).

practice a higher temperature will result in a higher eutectic starting temperature and will decrease the undercooling both for nucleation and growth.

3.2. Influence of pouring temperature on the volume changes of the mushy zone and casting (for the case of the linear nucleation law)

It is evident that the pouring temperature strongly influences the liquid contraction of the melt as shown in Fig. 14. The higher the pouring temperature is the more liquid contraction there will be. Since the large liquid contraction needs a large quantity of feeding melt for compensation it will tend to form porosity in the casting with a higher pouring temperature. However, the relative expansions during the eutectic reaction have nearly the same value for both cases since the same eutectic temperature for both pouring temperatures is assumed. In practice, a higher pouring temperature will result in a higher eutectic starting temperature or a decrease of the undercooling both

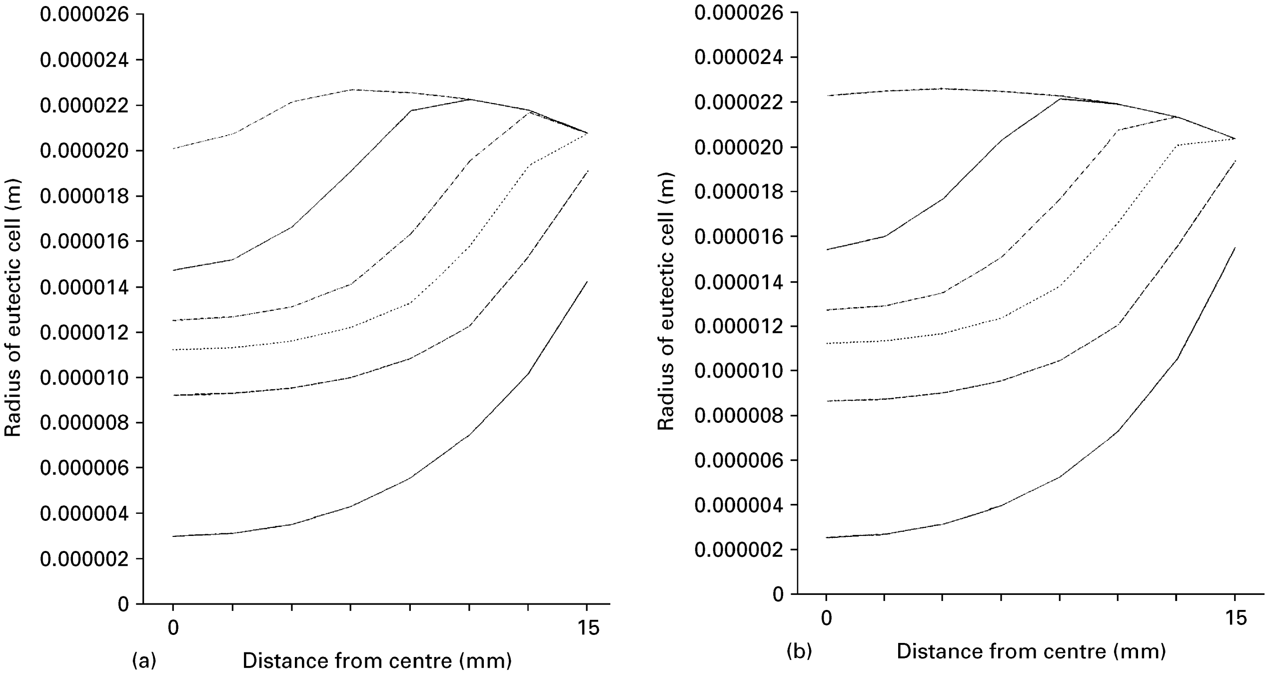

Figure 13 Influence of pouring temperature (TP) on the radius of the eutectic cell. (a) $A = 10 \times 10^{11}$, TP = 1350 °C (Key: —— 56 s; – – – 76 s; · · · · · 96 s; – · – · – 116 s; —— 146 s; – · · – · · – 171 s). (b) $A = 10 \times 10^{11}$, TP = 1250 °C (Key: —— 31 s; – – – 46 s; · · · · 66 s; – · – · – 86 s; —— 111 s; – · · – · · – 136 s).

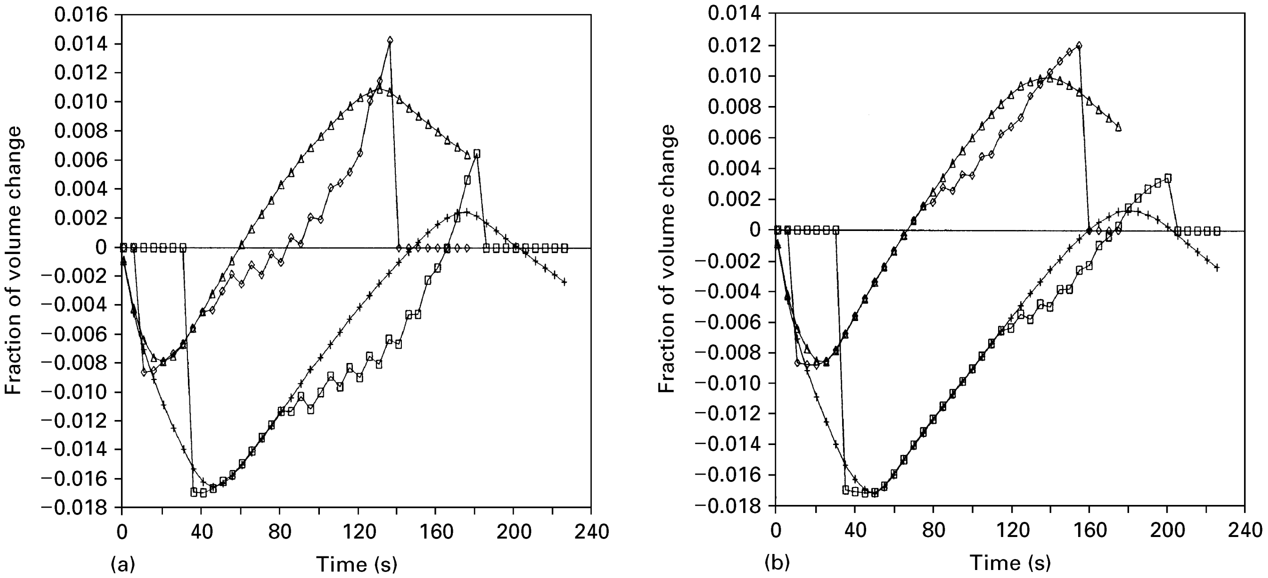

Figure 14 Influence of pouring temperature on the volume changes of the mushy zone and casting (for the linear nucleation law). (a) $A = 10 \times 10^{11}$ and (b) $A = 1 \times 10^{11}$ (key: □ M, TP = 1350 °C + C, TP = 1350 °C; ◇ M, TP = 1250 °C; △ C, TP = 1250 °C).

for nucleation and growth and make a relative larger expansion. The relationship between the pouring temperature and the eutectic starting temperature depends on the thermal properties of the actual mould material. If this relationship can be found the influence of pouring temperature on the volume change during the eutectic reaction can be simulated accurately.

3.3. Influence of pouring temperature on the volume changes of the mushy zone and casting (for the case of the quadratic nucleation law)

Influence of pouring temperature on the volume changes of the mushy zone and casting with the quadratic nucleation law (see also [2]) is shown in Fig. 15. The trend is the same as that seen with the linear nucleation law.

4. Influence of heat transfer coefficient on the volume change during the solidification

The influence of heat transfer coefficient ($h_{\text{interface}}$) on the volume change during the solidification is shown in Fig. 16 for different nucleation constants. It is seen that the heat transfer coefficient has no influence on the volume changes of the mushy zone and casting. This is because the eutectic reactions for both cases occur at the same eutectic temperature (for a given

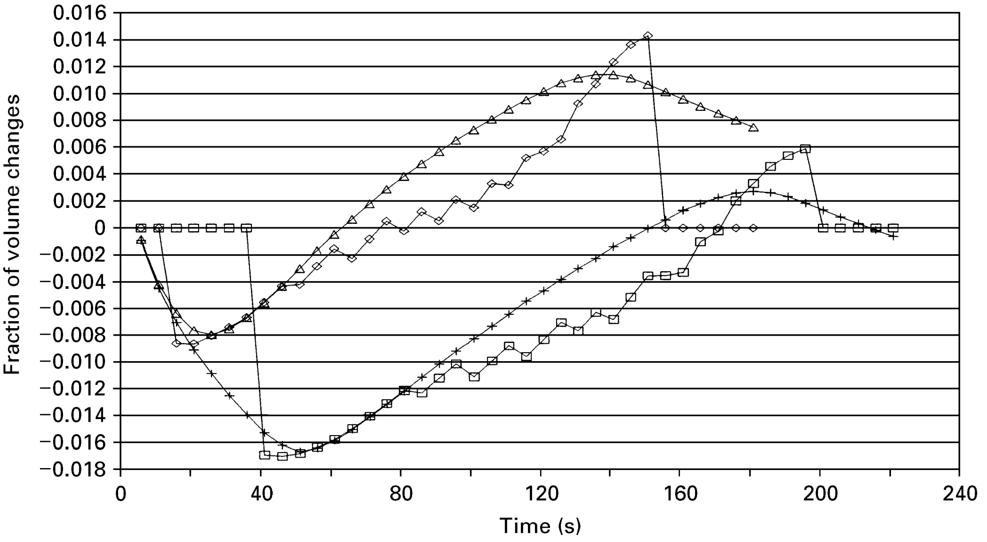

Figure 15 Influence of pouring temperature on the volume changes of the mushy zone and casting (for the quadratic nucleation law): $A = 1 \times 10^{11}$; □ M, TP = 1350 °C; + C, TP = 1350 °C; ◇ M, TP = 1250 °C; △ C, TP = 1250 °C.

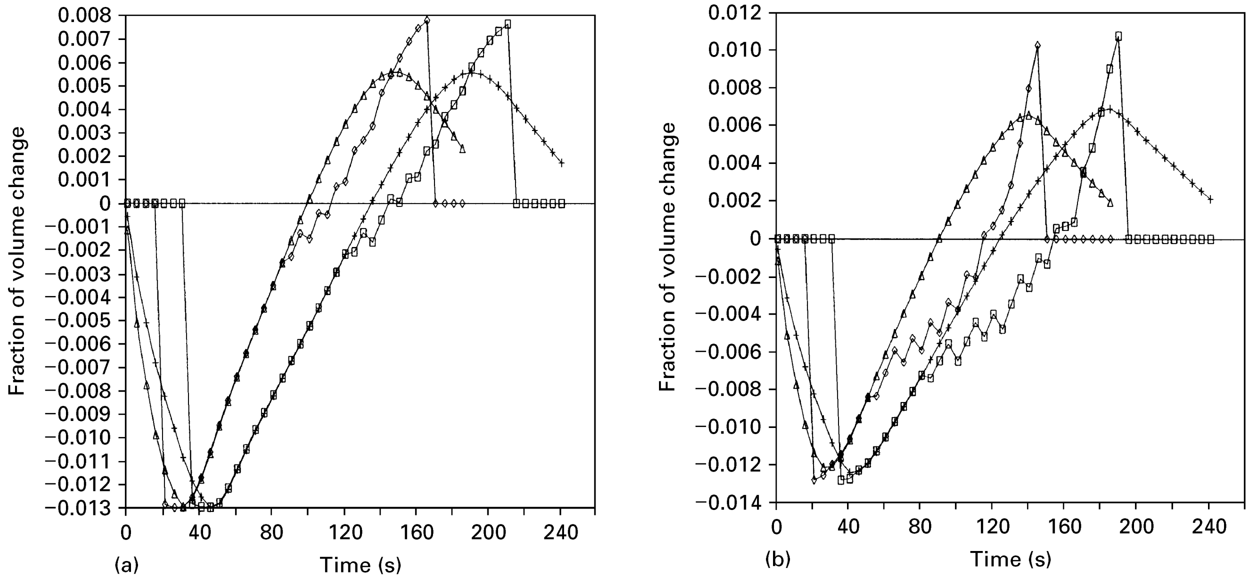

Figure 16 Influence of heat transfer coefficient ($h_{interface}$) on the volume change during the solidification. (a) $A = 1 \times 10^{11}$ and (b) $A = 10 \times 10^{11}$. Key: □ M, $h = 500$; + C, $h = 500$; ◇M, $h = 1500$; △ C, $h = 1500$.

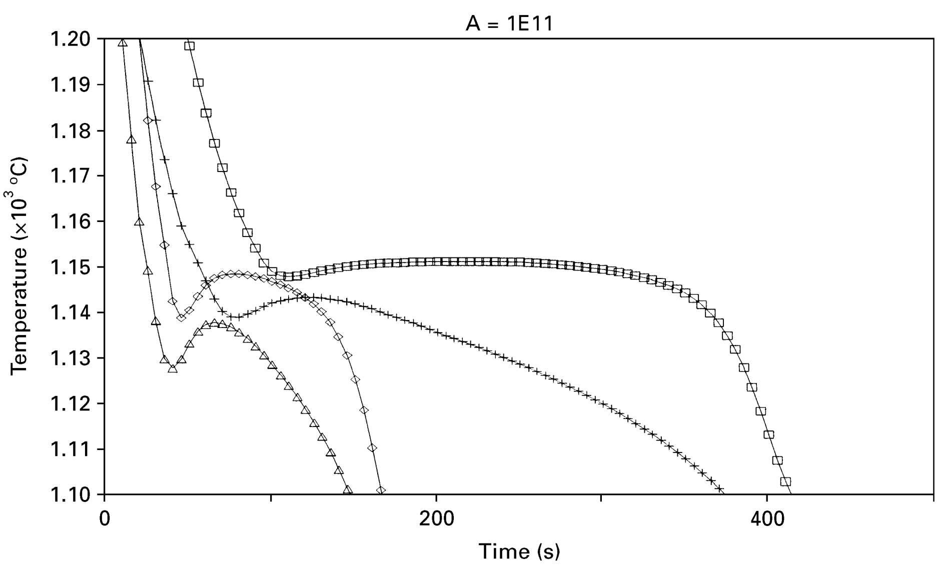

Figure 17 Cooling curves for the different elements and the different sizes of castings. $A = 1 \times 10^{11}$. Key: □ $R = 25$, centre, + surface; ◇ $R = 15$, centre; △ surface.

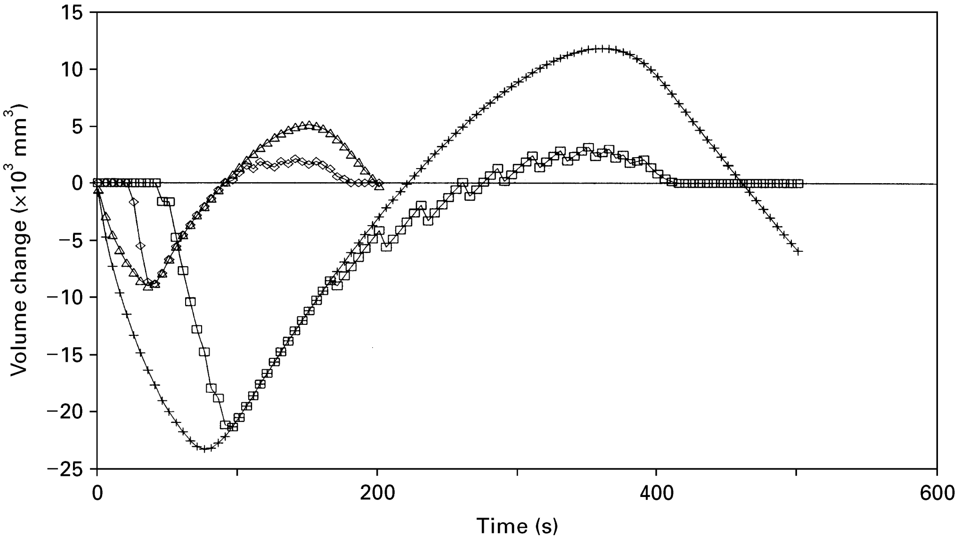

Figure 18 Absolute changes of the castings with different radii ($R = 15$ mm and $R = 25$ mm). M means the mushy zone and C means casting. $A = 1 \times 10^{11}$. Key: □ M, R = 25 mm; + C; ◇ M, R = 15 mm; △ C.

nucleation constant) and the introduction of the latent heat is independent of the eutectic temperature. The volume change of the casting only depends on the temperature if Rappaz's growth model is used in the calculation (see [2]). However, in practice the heat transfer coefficient will influence the undercooling of the eutectic nucleation and growth. So it is important to find the correlation between them so that the calculation will be more reasonable and practical. The difference in the volume changes between the different nucleation constants is obvious and this can be explained by the views given in Section 2. However, a large heat transfer coefficient results in a decrease in freezing time and early completion of the volume change.

5. Influence of section size on the volume change of casting

A comparison between the cooling curves of different sizes of casting is shown in Fig. 17. The corresponding volume changes of casting are shown in Fig. 18. It is evident that the volume changes are related. The casting with large volume corresponds to a large volume change and vice versa. It can be expected that the large section will suffer a large contraction during the early stage of liquid cooling and a large expansion during the eutectic reaction. So it is probable that castings of large section will form a shrinkage cavity during solidification.

6. Conclusion

From the results of the simulation it is seen that the influence of inoculation is to decrease the eutectic undercooling and further to increase the specific volumes of the phases which form during the eutectic reaction. Strong inoculation results in a decrease of the volume of the mushy zone, which results in a decrease of the volume expansion of the mushy zone. A higher pouring temperature results in a large liquid contraction and increases the tendency of forming a shrinkage cavity in the casting. A large heat transfer coefficient results in a decrease in the solidification time and early completion of the volume change.

Acknowledgement

One of the authors (Qiming Chen) would like to acknowledge financial support from Daloon Fonden for this research.

References

1. QIMING CHEN, E. W. LANGER and P. N. HANSEN, *Scandinavian J. Metall.* **24** (1995) 48.
2. *Idem, ibid.* **24** (1995) 2.
3. M. TAFAZZOLI-YADZI and V. KONDIC, *AFS Int. Cast Metals J* **2** (1977) 41.
4. S. I. KARSAY, "Ductile Iron – The State of The Art" (Qit-Fer Et Titane Inc., Canada, 1980) p. 34.
5. J. LACAZE and P. ALEXANDRE, in "Mathematical Modelling for Materials Processing", edited by M. Cross, J. F. T. Pittman, R. Wood (Clarendon Press, Oxford, 1993) p. 211.
6. M. CASTRO, P. ALEXANDRE, J. LACAZE and G. LESOULT, Conference Proceedings, Cast Iron IV, (Materials Research Society, North Holland, 1990) p. 433.

Received 19 January
and accepted 17 September 1996