Leading Phase in the Directionally Solidifying Fe – 4.25%C Eutectic Alloy

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Abstract

In order to determine the leading phase of the Fe - 4.25% C eutectic alloy, the method of directional crystallization, which allows to study the character of the solid / liquid growth front, was used. Examined eutectic was directionally solidified with a constant temperature gradient of $G = 33,5$ K/mm and growth rate of $v = 125$ μm/s (450 mm/h). The Bridgman technique was used for the solidification process. The sample was grown by pulling it downwards up to 30 mm in length. The alloy quenched by rapid pulling down into the Ga-In-Sn liquid metal. The sample was examined on the longitudinal section using a light microscope and scanning electron microscope. The shape of the solid/liquid interface and particularly the leading phase protrusion were revealed. The formation of the concave – convex interface has been identified in the quasi-regular eutectic growth arrested by quenching. The cementite phase was determined to be a leading phase. The total protrusion d is marked in the adequate figure.

Keywords: Directional solidification, Fe - C eutectic alloy, Solidification front, Leading phase

1. Introduction

Morphological analysis of eutectic grains allows us to consider the concept of the leading phase. This is one of the key subjects of the theory of eutectic solidification. The Botschwar monograph [1] describes this phase as the leading phase of eutectic solidification. As well as the formation of eutectic grains due to the greater linear solidification rate and protrusion into liquid [2].

V.L. Davies [3] was pioneer in showing the role of leading phases in eutectic growth by the theoretical studies of formation of solid-liquid interface during unidirectional eutectic growth.

The directional solidification allows to thoroughly study the character of the solid/liquid growth front. In this method steady-state growth fronts are suddenly quenched. Along with high enough increase of rate upon quenching, a sudden change in the

microstructure occurs at the growth front. This allows to observe the growth front morphology [4]. The classical Jackson and Hunt [5] theory of the eutectic growth begins with solving the solute diffusion equation in front of a planar solid/liquid (s/l) interface moving in the z-direction at a constant v.

In studies [6-10], research on leading phase in eutectic was also undertaken.

The study of the process of eutectic grain nucleation and the characteristics of its structure allows to explain and extend the concept of the leading phase.

The growth of Fe(γ)-Fe₃C eutectic grain can be analysed on the basis of the eutectic formation mechanism. The basic property of this process is related to the layered growth of the leading phase, due to the anisotropy of interatomic bond forces. The solid/liquid interface morphology of hardened alloy appears to be smooth and has no leading branching of the leading phase.

However, a thorough analysis allows to present the protrusion and determine the distance of leading phase protrusion [2, 6].

Occurrence of protrusion does not indicate a different growth rate of eutectic phases. The analysis of the structure of hardened alloys showed, in the range of the entire eutectic transformation time, that the distance of the protrusion is unchanged since the formation of grain matrix, up to the end of the growth stage, until the chemical composition of small amounts of the liquid phase begins to change. Acceleration of the growth of one phase causes acceleration of the growth of branching of the second phase. Otherwise, the coupled nature of multiphase crystallization is violated [2, 6].

During regular eutectic growth, one of the phases is the leading phase. To determine this phase, the protrusion must be defined.

2. Experimental procedure

The Fe - 4,25wt % C eutectic alloy sample, made from Armco and graphite electrodes of high purity was prepared in a graphite crucible under the protection of argon gas in Balzers-type heater.

After removing the dross and thermal stabilization the molten alloy was poured into a permanent mold and cast into rod of 12 mm diameter. Then the sample was machined, using a wire cutting process, to approximately 5 mm. The sample was:

a) positioned in an alunde tube with an inner diameter of 6 mm in the vacuum Bridgman-type furnace, under an argon atmosphere,
b) heated to a temperature of $1450^{o}C$,
c) lowered at a given rate from the heating part to the cooling part of the furnace, after stabilizing the thermal conditions,
d) grown by pulling it downwards at a constant pulling rate v=125 μm/s and at a constant temperature gradient G=33.5 K/mm up to 30 mm in length,
e) quenched by rapid pulling down into the Ga-In-Sn liquid metal.

The experimental procedure is defined in more detail in [11, 12]. And studies on the directional solidification of this alloy are described in [13, 14]

The research of directional solidification was performed in the Department of Casting at the AGH University of Science and Technology in Krakow.

Chemical composition of Fe – 4.25% C alloy is shown in Table 1. Figure 1 presents researched rod sample.

Fig. 1. Researched, directionally solidified sample

Table 1.
Chemical composition of Fe – 4.25% C alloy [wt. %]

C	Si	Mn	P	S	Cr	Ni	Mo	Al	Cu
4.25	0.057	0.64	0.0079	0.021	0.033	0.0093	<0.0020	0.011	0.032
Co	**Ti**	**Ni**	**Nb**	**V**	**W**	**Pb**	**Mg**	**B**	**Sn**
0.0024	<0.0010	0.0093	<0.0040	0.0022	<0.010	<0.0030	<0.0010	0.0009	0.0061
Zn	**As**	**Bi**	**Ca**	**Ce**	**Zr**	**La**	**Fe**		
<0.0020	0.0069	<0.0020	0.0005	<0.0030	0.0043	0.0013	94.9		

3. Experimental results

Figure 2 shows solid/liquid interface morphology of directionally solidified Fe-4.25%C eutectic alloy in sample of 5 mm diameter.

Figure 3 shows longitudinal section microstructure during directional solidification of the Fe-4.25%C eutectic alloy.

In Figure 4 concave-convex shape of the Fe-4.25%C eutectic interface is marked.

Fig. 2. Solidification front in Fe-4.25%C sample of 5 mm diameter, solidified directionally at 125 μm/s and G=33.5 K/mm, x 2
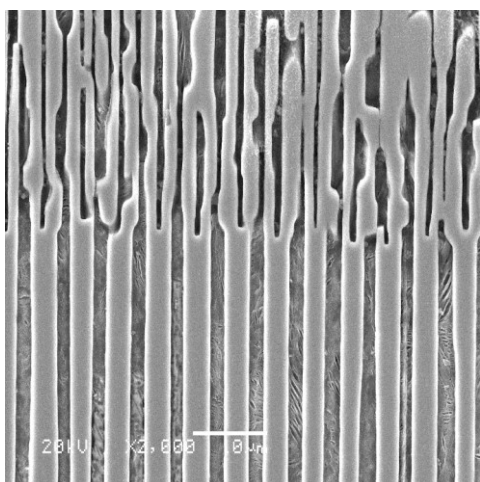

Fig. 3. Fe-4.25%C eutectic morphology at the quenching interface on the longitudinal section, SEM

Figure 5 indicates parameters of quasi-regular Fe-4.25%C eutectic alloy: $2S_{Fe_3C}$ - the thickness of the cementite phase lamellae, $2S_{Fe(\gamma)}$ - the thickness of the austenite phase, d_{Fe_3C} - concave protrusion of Fe_3C phase, $d_{Fe(\gamma)}$ - convexity retraction of austenite phase.

4. Discussion

In Figure 2, showing the solid/liquid interface morphology, the front is planar in the central region.

Figure 3 shows longitudinal section microstructure of directionally solidified Fe - 4.25%C eutectic alloy. Parallel, bright cementite lamellae were observed, between which there is a pearlite (austenite) phase. At the quenching interface, the eutectic lamellar spacing decreased quickly due to the mechanism of lamellar branching caused by a sudden increase of the cooling rate.
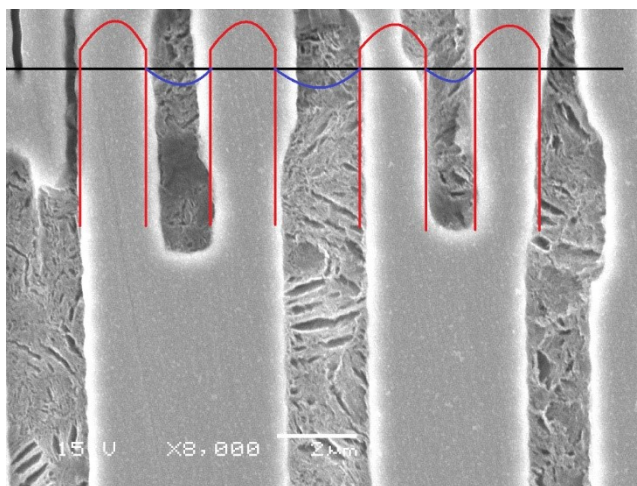

Fig. 4. Concave-convex shape of the Fe-4.25%C eutectic interface and outline of the protrusion of Fe_3C – leading phase (red line); the austenite Fe(γ) (pearlite) – phase is determined as a wetting phase (blue line), SEM
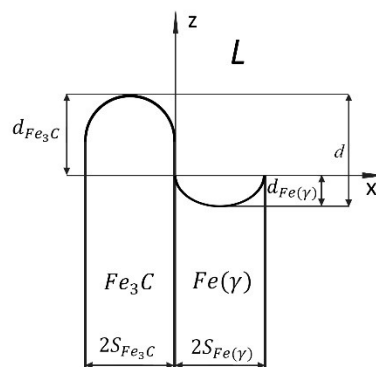

Fig. 5. The parameters of solidification front of quasi-regular Fe-4.25%C eutectic alloy: d_{Fe_3C} - convexity of cementite phase, $d_{Fe(\gamma)}$ - concave of austenite phase, d - total protrusion of Fe_3C phase

Figure 3 shows the structure of oriented eutectics (in the lower part) obtained at a given solidification rate. In its upper part, separated from the lower part by a planar solidification front (in the macro scale), the eutectic oriented structure is also clearly visible. However, it formed with at least twice the solidification speed caused by rapid cooling. It can be concluded that stopping the solidification process by freezing the front and the remaining liquid phase was not very successful. However, it allowed to obtain an interesting result consisting in decreasing the thickness of the oriented structure.

The planar front on the macro scale, which is quite clearly visible in Fig. 3, is also noticeable in Fig. 4.

In Figure 4 the shape of the cementite lamellae is marked in red and the shape of the austenite phase (pearlite) in blue. There was a protrusion of the cementite (red line) in relation to austenite phase (pearlite) (blue line).

In the experiment, the cementite phase was thickened already in the solid state (below the solidification front) by means of an appropriate phase transformation. At the same time, austenite was transformed into perlite in the austenitic phase lamellae, which on this occasion became thinner. This is proved by the proportion of the width of the tiles presented in Fig. 4. The sudden change in the solidification rate by the use of rapid cooling apparently caused the formation of an eutectic oriented structure in which the plates of both phases are about the same thickness, as suggested by the iron-cementite phase diagram analysis. It can be assumed that at such an increased solidification rate, there was no such intensive thickening of cementite plates in solid state or that this phenomenon was completely eliminated.

Given that generally the dimensions of the leading phase are smaller than the wetting phase to be concluded that the leading phase of researched alloy is a cementite phase (Fig. 4).

In Figure 5 the thickness of austenite phase (pearlite) - $2S_{Fe(\gamma)}$ is greater than the thickness of the cementite phase lamellae – $2S_{Fe_3C}$. Both, the convexity of d_{Fe_3C} cementite phase and concave of austenite phase - $d_{Fe(\gamma)}$, are marked.

The convexity of d_{Fe_3C} cementite phase indicates that cementite is the leading phase in the studied eutectic alloy. This is consistent with the literature [2, 4, 7, 15÷18] and the observation for the white cast iron.

5. Conclusions

In researched quasi-regular Fe-4.25%C eutectic alloy, directionally solidified with a constant temperature gradient of $G = 33.5$ K/mm and growth rate of $v = 125$ μm/s (450 mm/h), the concave-convex interface shape formation has been observed.

The total protrusion d (Fig.5) is therefore:

$$d = d_{Fe_3C} + d_{Fe(\gamma)}$$

Revealing the protrusion of lamellae of Fe$_3$C this phase was determined to be the leading phase; whereas - the austenite (pearlite) phase is determined as a wetting phase.

Acknowledgements

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