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On the stable eutectic solidification of iron–carbon–silicon alloys

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ABSTRACT

Extensive effort was expanded to elucidate the growth and morphology of the stable eutectic grains during early solidification of continuous cooled Fe–C–Si alloys. To this purpose, quenching experiments at successive stages during solidification have been carried out on five cast irons with various magnesium and titanium levels designed to produce graphite morphologies ranging from lamellar to mixed compacted–spheroidal.

The graphite shape factors were measured on the metallographic samples, and their evolution as a function of the chemical composition and the solid fraction was analyzed. Extensive scanning electron microscopy was carried on to evaluate the change in graphite shape during early solidification, to establish the fraction of solid at which the transition from spheroidal-to-compacted-to-lamellar graphite occurs, and to outline the early morphology of the eutectic grains. It was confirmed that solidification of Mg containing irons started with the development of spheroidal graphite even at Mg levels as low as 0.013 mass%. Then, as solidification proceeds, when some spheroids developed one or more tails (tadpole graphite), the spheroidal-to-compacted graphite transition occurs.

The new findings were then integrated in previous knowledge to produce an understanding of the eutectic solidification of these materials. It was concluded that in hypoeutectic lamellar graphite iron austenite/graphite eutectic grains can nucleate at the austenite/liquid interface or in the bulk of the liquid, depending on the sulfur content and on the cooling rate. When graphite nucleation occurs on the primary austenite, several eutectic grains can nucleate and grow on the same dendrite. The primary austenite continues growing as eutectic austenite and therefore the two have the same crystallographic orientation. Thus, a final austenite grain may include several eutectic grains. In eutectic irons the eutectic grains nucleate and grow mostly in the liquid. The eutectic austenite has different crystallographic orientation than the primary one.

The solidification of the austenite/spheroidal graphite eutectic is divorced, with graphite spheroids growing on primary austenite dendrites. The eutectic austenite grows on the primary austenite and has the same crystallographic orientation. The result is large austenite (primary and eutectic) dendrites that incorporate numerous graphite spheroids. A eutectic grain cannot be defined.

1. Introduction

Cast iron is a multicomponent Fe–C based alloy (Fe–C–Si–Mn–S-etc.) that solidifies with a eutectic. Although cast iron use in the panoply of materials employed by humans dates as far back as 502 B.C., and in spite of the extensive research started at the beginning of the 18th century that continues to these days, the mechanism of the stable (gray) eutectic solidification in lamellar, compacted, and spheroidal graphite iron is not fully understood. Complications arise from the fact that, in directional solidification, microstructure formation is controlled by the thermal gradient/solidification velocity (G/V) ratio, while in continuous cooling solidification, typical for most industrial shape casting processes, the controlling factor is the $G{\cdot}V$ product, which is the cooling rate.

As early as 1960, interrupted solidification experiments (quenching in water) performed by Oldfield [1] demonstrated that the eutectic solidification of lamellar graphite (LG) iron starts with quasi-spherical grains of graphite lamellae and eutectic austenite (γ) that grow radially from a common center (Fig. 1). Direct evidence of the quasi-spherical shape of the γ/LG eutectic grains was also provided by Motz [2] who was able to decant the grains from the solidifying liquid.

A similar morphology of the eutectic grain was postulated by Lakeland and Hogan [3] who performed the first directional solid-

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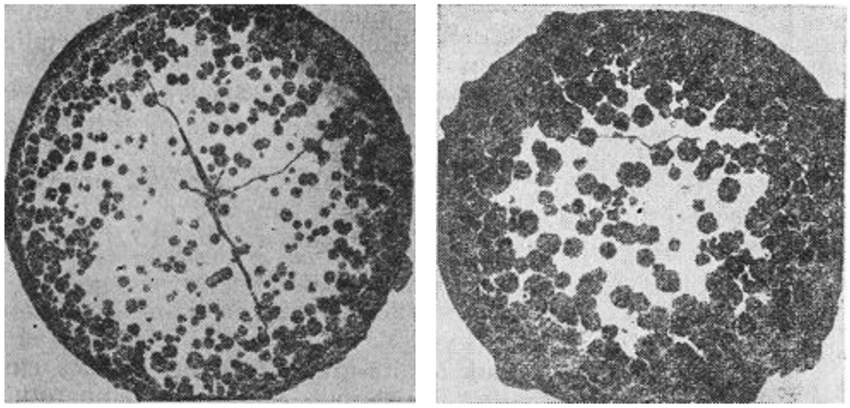


Fig. 1. Macrostructure of interrupted solidification of rods showing spherical eutectic grain growth at two consecutive times during solidification [1].

ification (DS) experiments on cast iron. According to these authors, once the spherical eutectic grains (A, B, C in Fig. 2) started growing, heterogeneous nucleation of austenite occurs (a, b) and austenite dendrites grow into the melt.

The eutectic grain macrostructure of LG iron can be visualized by using selective etching (e.g., Stead's reagent) to outline the phosphide eutectic which is the last to solidify, and therefore delineates the solidification grain boundaries. In the old and/or industrial patois the eutectic grains are also termed "eutectic cells" or "eutectic colonies". This terminology is inconsistent with the modern vocabulary of solidification science. It should be avoided as it creates confusion with cellular solidification of single phase alloys.

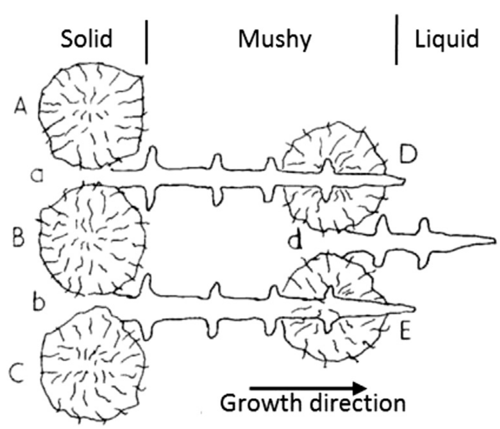
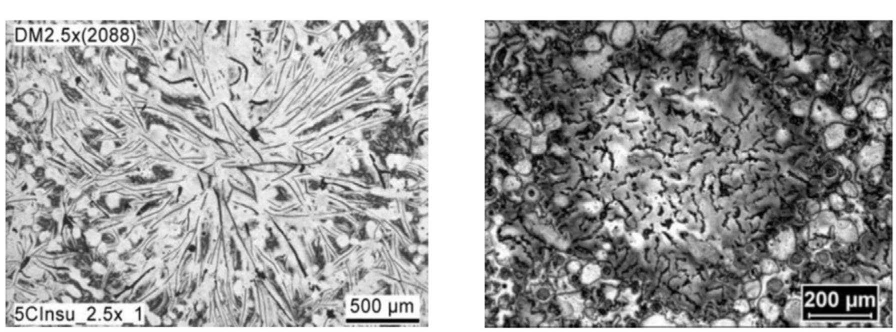


Fig. 2. Growth of the irregular solid/liquid interface in LG iron [2].

The room temperature microstructure of the eutectic grains of lamellar and low nodularity compacted graphite iron are shown in Fig. 3 [4,5]. They have a quasi-spherical appearance.

For spheroidal graphite (SG) iron, Ellerbrok and Engler [6,7] described as early as 1981 the two important features of its eutectic solidification, namely the dendritic nature of the eutectic with several graphite spheroids within each austenite dendrite, and the mushy type of solidification (Fig. 4). Following the directional solidification experiments by Lakeland and Hogan [3], Argo and Gruzleski [8], and Bandyopadhyay et al. [9] a clear picture of the solidification structural transitions of cast iron imposed by the G/V ratio and composition became available. They were summarized in 1988 as sown in Fig. 5a [10]. It is seen that as the G/V ratio decreases, or the composition C_o (e.g., Mg or Ce) increases from right to left, the solid/liquid (S/L) interface changes from planar, to cellular, and then to equiaxed, while graphite remains lamellar. Cooperative growth of austenite and graphite occurs. Further decrease in G/V or increase of C_o brings about formation of an irregular interface, with austenite dendrites protruding in the liquid. Graphite becomes compacted and then spheroidal. Eutectic growth is divorced. The drawing also suggests that some austenitic shell may develop around the graphite spheroids before any contact with the primary austenite.

The proposed sequence was confirmed two years later by interrupted DS experiments [11] summarized in Fig. 5b. Note that SG iron solidifies with an austenite/dendritic interface that incorporates graphite nodules. CG iron shows an austenite/cellular interface that includes the CG. In both cases the leading phase is the austenite. LG iron solidifies with a rather flat interface where graphite and austenite grow cooperatively with the graphite being the leading phase.



a) lamellar graphite eutectic grain [4] b) compacted graphite eutectic grain [5]

Fig. 3. Eutectic grains in cast iron. Original pictures are color etched.