Modelling the concentration and dimensional changes in the structural constituents of vermicular graphite cast iron on cooling within the range of solidus-eutectoid temperature

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Abstract

A mathematical model and a simulation program have been developed to trace changes in the structure of Fe-C alloy on cooling from the solidus temperature to the temperature of eutectoid transformation. A simplified schematic representation of the process can be referred to the cast iron with vermicular graphite. The numerical experiments using the newly developed program have proved a significant effect of the cooling conditions and structure refinement degree (the dimensions of austenite) on the concentration field in austenite and, consequently, on the dimensional changes of graphite within the examined cooling range. The developed methods of modelling the process of transformation enable including the procedure into a complex software operating in a system reproducing in real manner the casting configuration, while the obtained results indicate an important effect of thermophysical parameters and heat transfer process on final alloy structure.

Keywords: Modelling; Cast iron; Solid state; Graphite; Austenite

1. Introduction

The vermicular graphite (i.e. the „worm-like”-shaped graphite) was first observed in castings made from the nodular graphite iron when either the amount of the nodulariser introduced to cast iron was insufficient or partial fading of the treatment effect occurred. This form of graphite was at the beginning treated as an undesired constituent of cast iron, Practical use of the specific properties of the cast iron with this graphite took place in 1955, the name “vermicular graphite” being proposed by Shelleng in 1960 (a British patent). Today, numerous publications that appear on this subject use rather the name of compacted graphite [1]. The present state of the technology related with the production of vermicular graphite cast iron was described in [2]. The opportunities that exist for this grade of cast iron due to the development of SinterCast technology ensuring high-quality material were disclosed by Lampic [3]. Recently, the mechanical properties of the vermicular graphite cast iron much higher than those of the grey cast iron with flake graphite have been observed during measurement of micro-stresses related with different shapes and dimensions of the graphite particles [4].
The search for possible means of improving the cast iron properties includes additional heat treatment, especially the operation of the, so called, austempering, known also as an ausferritising process. The aim of this process is to change the cast iron matrix in which the initial structure of a pearlitic, pearlitic-ferritic, ferritic-pearlitic, or totally ferritic type produced after the preliminary austenitising process acquires, due to austempering, its final form of ausferrite with high-carbon lamellae of austenite arranged alternately with the lamellae of high-carbon ferrite.

The most commonly applied operation of ausferritising is the process conducted nowadays on ductile iron. Its outcome is fabrication of material called ADI (Austempered Ductile Iron), the three-letter acronym being widely used in the Polish language, too. In Polish, they also use the term "ausferritic cast iron", originating from a typical matrix structure present in this material. In Polish technical literature, the technology of ADI fabrication has been described most comprehensively in [2].

Trials on the process of the ausferritising treatment were conducted also on grey cast iron (AGI – Austempered Grey Iron) and malleable cast iron (AMI – Austempered Malleable Iron) [5], but the best chances for success has the process conducted on cast iron with vermicular/compacted graphite (ACI – Austempered Compacted Iron [6 – 10] or AVI – Austempered Vermicular Iron [11]).

It seems quite obvious that as regards computer modelling of phase transformations, the studies have been undertaken on one of the best known cast irons, i.e. the austempered ductile iron ADI [12 13 14 15]. This fact is well justified by searching for a possibility of having an optimum control of this technology. AGI is thought to stand but only very small chances for any wider application, because at the same cost of heat treatment one can obtain much better results using as a base material the cast iron with nodular graphite (for ADI) or vermicular graphite (for AVI).

The aim of the present study is to develop a model and a numerical program to compute the kinetics of changes in the carbon concentration field and in the dimensions of graphite precipitates on cooling of the casting from the point of solidus to the temperature of eutectoid transformation.

2. Model of the process

The structure of the vermicular graphite cast iron is shown in Figure 1.

In the model, the following assumptions have been made:
- the sample (casting) from Fe-C alloy has a preset cooling rate from the eutectic temperature to the eutectoid one;
- change of thermodynamic conditions caused by temperature changes takes place in an Fe-C system; the effect of other elements is disregarded;
- because of changes in thermodynamic conditions, carbon concentration gradients occur, and mass diffusion caused by these gradients is the driving force for a movement of the austenite-graphite interface;
- a unidimensional concentration system with planar interface surface is adopted.

Fig. 1. Vermicular cast iron structure [16]

A schematic representation of the concentration field is shown in Fig. 2a, and it is compared with the schematic representation of a phase equilibrium diagram in Fig. 2b.

Fig. 2. Schematic representation of the distribution of constituents concentration in austenite-graphite system compared with a phase equilibrium diagram

2.1. The system of equations

The concentration field in the examined system is described by the following equation:

$$\frac{dC}{d\tau} = \frac{\partial C}{\partial x} \left( \frac{dx}{d\tau} \right) + \frac{\partial C}{\partial \tau}$$

where: $\partial C/\partial \tau$ – is taken from the Fick’s equation for a fixed interface:

$$\frac{\partial C}{\partial \tau} = D \frac{\partial^2 C}{\partial x^2}$$

where: $D$ – is the coefficient of carbon diffusion in austenite.

The term in material (substantial) derivative $dx/d\tau$ is the velocity of the interface movement $u$, which can be determined from the following balance equation (Fig. 2):
The above system of equations was solved by the finite difference method using the procedure of a moving network, described in [17].

3. The results of modelling

The developed program enables numerical experiments to be made on the process running with different starting dimensions of austenite and at different cooling rates. The dimension of an elementary diffusion field (EDF) in austenite $X_Y$ (Fig. 2) is counted as a half-distance between the neighboring precipitates of graphite and is directly related with the number of these precipitates.

Figure 3 shows the distribution of carbon concentration values in EDF around the graphite precipitates under the assumption that the cooling rate is 1 K/s and the austenite layer thickness is 0.01 cm. Under these conditions, the distribution of carbon concentrations is almost uniform and practically does not deviate from the carbon content determined by the line $E'S'$ in phase equilibrium diagram (Fig. 2b).

![Diagram 3](image3.png)

Fig. 3. Carbon concentration in EDF for the austenite layer thickness of 0.01 cm and the cooling rate of 1K/s

Making the austenite layer thicker changes the concentration field (Fig. 4). It is worth noting that, in spite of the alloy cooling within the range of eutectic/eutectoid transformation temperatures, a tenfold increase in the austenite layer thickness does not change the carbon concentration in austenite in the region most remote from the surface of graphite.

Compared with previous cases (Figs. 3 and 4), increasing the cooling rate up to 10 K/s (for the austenite layer thickness of 0.01 cm) – Fig. 5 – gives an intermediate effect for the concentration field.

The diffusion, caused by the reduced carbon solubility in austenite during casting cooling, promotes movement of the austenite-graphite interface. The velocity of migration of this interface depends on process conditions. For the conditions of UT = 1 K/s; $X_Y = 0.01$ cm (Fig. 6, curve 1), the velocity of the interface migration is practically stable. For the same cooling rate (UT = 1 K/s, curve 2), increasing the thickness of an austenite layer to 0.1 cm increases the interface velocity due to a change in the concentration field (Figs. 3 and 4). At a tenfold increase of the cooling rate (UT = 10 K/s), the velocity of the interface migration increases quite considerably, but the increase is not proportional to the increase of the cooling rate (Fig. 6, curve 3).

![Diagram 4](image4.png)

Fig. 4. Carbon concentration in EDF for the austenite layer thickness of 0.1 cm and the cooling rate of 1K/s

![Diagram 5](image5.png)

Fig. 5. Carbon concentration in EDF for the austenite layer thickness of 0.01 cm and the cooling rate of 10 K/s

![Diagram 6](image6.png)

Fig. 6. Austenite-graphite interface migration velocity for different austenite dimensions and different cooling conditions

The change in graphite-austenite thickness relationship is shown in Figure 7. The kinetics of changes in phase dimensions in
relation to the process conditions discussed above is now well visible.

**Fig. 7.** Change in graphite-austenite thickness relationship during alloy cooling

In view of relatively small graphite dimensions in respect of the austenite dimensions, the effect of dimensional changes is particularly well visible in graphite – Fig. 8. The greatest increase in graphite thickness is observed at a low casting cooling rate and small dimensions of austenite (curve 1, Fig. 8). Increasing the cooling rate (in the case under consideration from 1 to 10 K/s) results in a small increase of the graphite thickness only (curve 3). Increasing the austenite thickness from 0.01 to 0.1 cm and preserving the same cooling rate gives an intermediate result (curve 2, Fig. 8).

**Fig. 8.** Change of graphite thickness during cooling of alloy

### 4. Conclusions

A mathematical model and a simulation program have been developed to trace changes in the structure of Fe-C alloy on cooling from the solidus temperature to the temperature of eutectoid transformation. A simplified schematic representation of the process can be referred to the cast iron with vermicular graphite.

The numerical experiments using the newly developed program have proved a significant effect of the cooling conditions and structure refinement degree (the dimensions of austenite) on the concentration field in austenite and, consequently, on the dimensional changes of graphite within the examined cooling range.

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### References


