1. Introduction

Ductile iron characterize high sensitivity on cooling rate what in consequence leads to structural gradients. As a result there are continuous changes of structural features of cast iron with changes of its properties accordingly.

It has been proved that it is possible to produce thin wall ductile iron (TWDI) with wall thickness even below 3 mm (without chills, cold laps and misruns). TWDI can be lighter than their substitute made of aluminum alloys and characterized similar or better mechanical properties, definitely better dumping capacity. From an economics point of view costs involved in producing ductile iron is much lower than the ones corresponding to Al alloys. All the technological aspects involved in the production of thin wall ductile iron castings, should have been worked out before considering the development aluminum alloys castings as cast iron substitutes.

Numerous studies have been published on thin wall ductile iron, particularly on the solidification morphologies, microstructure characterization, carbide formation factors, production, mould filling and thermal analysis. Moreover, various experimental relationships have been developed between the chemical composition, pouring temperature, spheroidization and inoculation practice, casting geometry, plate thickness and mould materials. Yet, most of these works are limited to simple plate shaped castings.

Casting with the shape of Archimedes spiral can be used to analyze technological features of ductile iron as well as the kinetics of solidification. In TWDI castings the first stage of metal cooling is of great importance. This stage embraces metal cooling from pouring temperature to the onset of the solidification process. Pouring temperature (in mould represented by initial temperature of liquid metal) and also its further drop as a result of intensive heat transfer between the flowing metal stream—the mould material. Thermal analysis along with microstructure observations were made and show reasonable agreement of numerical calculations with experimental measurements.

KEY WORDS: ductile iron; thin wall castings; thermal analysis; numerical simulation.

2. Experimental

A modeling lay-out was designed for thin wall castings. Modeling lay-out, which is shown in Fig. 1(a), consist of gating system and Archimedes spirals with 1.5 m length and 0.001/H110030.015 m, 0.002/H110030.015 m and 0.003/H110030.015 m sections, respectively. Common gating system enabled simultaneously filling spiral cavities with different wall thickness. Ductile iron employed in the present work was produced in a medium-frequency induction furnace of 15 kg capacity. The raw materials were Sorelmetal, commercially pure silicon, and steel scrap. The metal was preheated at 1450°C and then poured into the mould. Spheroidization and inoculation processes were made in the mould, which was equipped with a reaction chamber containing a mixture of 0.85% spheroidizer (44–48% Si, 5–6% Mg, 0.25–0.4% La, 0.8–1.2% Al, 0.4–0.6% Ca) and 0.5% of inoculant (73–78% Si, 0.75–1.25% Ca, 0.75–1.25% Ba, 0.75–1.25% Al) connected to a mixing basin. In addition, post-inoculation occur in the mixing basin by introducing 0.1% of inoculant. The role of the mixing basin is to ensure that com-
Complete mixing of the liquid iron occurs after dissolution of the magnesium and inoculant alloys. Just after filling the mixing basin, a graphite plug is removed to enable metal flow into the mould cavity reproducing Archimedes spirals with 1.5 m length and different wall thickness (Fig. 1(a)). The chemical composition of the produced ductile irons was 3.60% C; 3.10% Si; 0.03% Mn; 0.025% P; 0.01% S; and 0.039% Mg.

Temperature of metal in mould cavity was estimated using unsheathed thermoelements wires in regular 0.1 m distances. Flooding metal stream in mold cavity closes circuit of unsheathed thermoelements wires (K type) with thickness of 0.2 mm connected to the digital data acquisition system (AGILENT 34970 A). In Fig. 1(b) it is shown castings of Archimedes spirals with wall thickness of 0.001, 0.002 and 0.003 m. Castability of tested cast iron for wall thickness 3 mm was 0.86 m.

3. Microstructure

Characterization of graphite morphology and matrix microstructure was performed on cross sections at different distance from the beginning of the spiral. The graphite morphology was characterized using image analysis software Leica QWin (v 3.5.0). The two dimensional spatial size distribution of nodules was converted to a three dimensional size distribution using Wiencek22) equation. In Fig. 2 there are presented microphotographs of structure as a function of spiral length.

Results of metallographic experiments along with results from thermal analysis are summarized in Table 1.

From analysis of the graphite distribution (an example of typical histogram is shown in Fig. 3) result that bimodal histogram represents graphite morphology. From metallographic analysis estimation of average radii of eutectic ($R_e$) and primary (large) graphite ($R_g$) were made (see Table 1). The presence of large nodules indicates that they have nucleated before the eutectic part of the solidification and by that had longer time to grow. As the growth is controlled by diffusion, a higher cooling rate will require a higher number of primary graphite nodules. This means that primary graphite nodule count increases as distance from the inlet increases (higher cooling rate). As a result of turbulent fluid flow of liquid metal larger nodules can be dragged by metal stream and in consequence number of primary graphite nodules can increase more pronounced with increasing distance from the inlet to the mould cavity.

The main group of the nodules has nucleated during the eutectic part of the solidification. As the distance from the inlet increases initial temperature of metal decreases (see Table 1). As a consequence cooling rate (near eutectic equilibrium temperature) and maximum undercooling at the onset of eutectic solidification increases, cause increase in graphite nodule count ($N_g$ and $N_e$). Summing up fluid flow
can affect nodule count distribution (Fig. 3) especially by increasing second group of nodules that is primary graphite. Microstructure is of pearlitic–ferritic matrix, free from chills. Near inlet there is almost ferritic matrix as a result of thermal heating from down-gate. As distance from inlet increases ferrite fraction ($f_f$) decreases (see Table 1).

From microstructure observations there are seen oval shaped spaces surrounded by graphite nodules. They are believed to be remaining from austenite dendrites.

4. Numerical Simulation

Numerical simulation uses well known heat balance equation it the form of:

\[
\frac{dR_g}{dt} = \frac{1}{2\sqrt{\rho_g \Delta T}} \sqrt{\frac{2D}{\rho_g m_g} (C_o - C_e)} \tag{3}
\]

where: $D$, diffusion coefficient of carbon in liquid; and $\rho_g$ density of graphite.

After integration of Eq. (3) radius of the graphite is given by:

\[
R_g = \sqrt{\frac{2D}{\rho_g m_g} (C_o - C_e)} \sqrt{t} \tag{4}
\]

Using the relationship between the degree of undercooling ($\Delta T$) and the concentration difference ($\Delta C = C_o - C_e$) in the form (Fig. 4) $\Delta C = \Delta T/m_g$

we have:

\[
R_g = \sqrt{\frac{2D}{\rho_g m_g} \Delta T \sqrt{t}} \tag{5}
\]

and:

\[
\frac{dR_g}{dt} = \sqrt{\frac{2D}{\rho_g m_g} \Delta T} \tag{6}
\]

In a model, it is assumed instantaneous nucleation.\(^{27}\) Evolution of graphite fraction can be expressed by Eq. (7):

\[
\frac{df_f}{dt} = 4\pi N_g R_g \frac{dR_g}{dt} \tag{7}
\]

where: $N_g$ is the nodule count (of primary graphite).

Evolution of graphite fraction covers the period from undercooling below liquidus equilibrium temperature of graphite. This temperature is given by Eq. (2) in the form:\(^{23}\)

\[
T_g = C - 1.3 + 0.31\text{Si} + 0.33\text{P} \frac{2.5710^{-3}}{\rho v} \tag{2}
\]

The model describing the growth of graphite in liquid is given in work.\(^{23}\) This model is based on the assumption that the diffusion area is a space limited by two concentric spheres. The inner sphere coincides with the surface of a sphere of radius $R_g(t)$ and the outer radius amounts $R_o$.

Growth rate equation of graphite spheres in a liquid has the form of:

\[
\frac{dR_g}{dt} = \frac{1}{2\sqrt{\rho_g \Delta T}} \sqrt{\frac{2D}{\rho_g m_g} (C_o - C_e)} \tag{3}
\]

Stage I: The solidification of primary graphite. Stage II: Eutectic solidification. Stage III: The solidification of austenite in the form of dendrites.

Stage I

Solidification in ductile iron with hypereutectic composition (carbon equivalent $>4.26$) start with nucleation and growth of graphite spheres in the liquid after undercooling
content in graphite eutectic).

Stage II

This stage involves nucleation and growth in terms of undercooling below eutectic equilibrium temperature \((T_e)\):\(^{(24)}\)

\[
T_e = 1153.97 + 5.25Si - 14.88P \quad \text{..............(8)}
\]

Stage II will be divided into two periods.

Period I

After reaching the eutectic composition, just below the eutectic equilibrium temperature there is nucleation of austenite envelope on a primary graphite nodules and start the growth of globular eutectic on primary graphite. Growth of austenite envelope is given by the equation\(^{(25)}\):

\[
(C_4 - C_3) \frac{dR_3}{dt} = \frac{R_4(C_4 - C_3)}{(R_4 - R_3)R_4} D \quad \text{..............(9)}
\]

Where: \(C_2, C_4\): carbon content in austenite, at austenite/graphite and austenite/liquid interface respectively, \(C_3\): carbon content in bulk liquid and graphite, \(R_2, R_3, R_4\): radii of austenite envelope and eutectic graphite, respectively.

From the mass balance in the volume of \((4/3)pR_3^3\) the radius of graphite can be calculated from\(^{(25)}\):

\[
R_3^2(C_4 - C_3) = R_3^2(C_4 - C_{3e}) - R_2^2(C_3 - C_{3e}) \quad \text{..............(10)}
\]

Concentrations \(C_2, C_3, C_4\) can be expressed as a function of undercooling. Assuming that the JE’, E’S’ and BC’ lines for the Fe–C system are straight, the compositions in Eq. (10) can be given by

\[
C_2 = C_4 + \frac{\Delta T}{m_2}, \quad C_3 = C_4 + \frac{\Delta T}{m_3}, \quad C_4 = C_4 + \frac{\Delta T}{m_4} \quad \text{..............(11)}
\]

where: \(C_{3e}, C_{4e}\) are respectively the concentration of carbon in the points E’ and C’ of Fe–C–Si system; \(m_2, m_3, m_4\) coefficients of directional lines, respectively E’S’, JE’ and BC’ in the Fe–C–Si system.

Evolution of austenite fraction can be given by Eq. (12):

\[
\frac{df_4}{dt} = 4\pi N_e R_4^2 \frac{dR_4}{dt} (1 - f_4) \quad \text{..............(12)}
\]

where: \(N_e\) is the nodule count (eutectic graphite nodules).

Equation (12) includes \((1 - f_4)\) term to account for grain impingement. This is called the correction factor due to slowdown in the growth impact of growing grain\(^{(26)}\).

Period 2

Period 2 in Stage II involves nucleation and growth of graphite eutectic nodules and nucleation and growth of austenite envelopes. Nucleus of eutectic graphite growth freely in liquid up to the dimension of the \(R_e\). In this period their growth is calculated using a similar procedure as for the primary graphite nodules taking into account undercooling below the extrapolated liquidus for graphite. Once the graphite is the radius amounted \(R_e\) there is diffusion controlled growth of graphite though austenite shell using Eqs. (9) and (10). Austenite envelope growth is calculated using an Eq. (12).

Stage III

Stage III involves nucleation and growth of austenite dendrites. This phase occurs after undercooling below extrapolated liquidus for austenite \((T_f)\). It is assumed instantaneous nucleation of austenite. Austenite liquidus is given by\(^{(25)}\):

\[
T_f = 1636 - 113(C + 0.25Si + 0.5P) \quad \text{..............(13)}
\]

In this paper, the growth of equiaxed austenite dendrites will be described by the relationship\(^{(27)}\):

\[
\frac{dR_d}{dt} = \mu \Delta T_f^3 \quad \text{..............(14)}
\]

where

\[
\mu = \frac{D_L}{2\pi^2Tm(k-1)c_L} \quad \text{..............(15)}
\]

\(R_d\): radius of austenite dendrite; \(D_L\): diffusion of carbon in austenite; \(T\): Gibbs–Thompson parameter; \(m\): liquidus slope lines for austenite in Fe–C system; \(C_L\): carbon concentration in liquid.

Evolution of austenite dendrite fraction can be given by Eq. (16):

\[
\frac{df_d}{dt} = 4\pi g_d N_d R_d^2 \frac{dR_d}{dt} (1 - f_d) \quad \text{..............(16)}
\]

where: \(N_d\): number of austenite dendrites; \(dR_d/dt\): growth rate of austenite dendrites. Equation (16) includes \((1 - f_d)\) to account for grain impingement. Spheres\(^{(28)}\) are not completely filled by the network-type dendrites. It is assumed that internal fraction of solid amounts \(g_d = 0.2–0.4\).

Matlab-Simulink™ (version R2009a) was used for numerical calculations of the solidification of a spiral-shaped TWDI casting with a wall thickness of 3 mm. With access to high-performance computing algorithms and mechanisms for analysis of Matlab-Simulink enable quickly and efficiently carry out complex calculations. Here are the method of numerical solving of differential equations and linear integration, differentiation, interpolation and approximation of functions and many others.

Numerical calculations were performed on the basis on data taken from experiments that are the initial temperatures of metal in mould and the results from metallographic
studies (such as the number of spheres of graphite). Experimental studies made it possible to obtain the actual cooling curves of ductile iron. Physical properties used in numerical modeling are summarized in Table 2.

5. Experimental Results and Discussion

In Fig. 5 there are shown cooling curves resulting from numerical modelling compared with experimental curves obtained at different distances from the beginning of the spiral. Results of computer simulation show fairly good compliance with the experimental results. Both numerical calculated and experimental curves show recalescence, that is, the temperature difference between the highest and lowest temperatures. However, the predicted recalescence is somewhat higher than determined by thermal analysis.

Flowing metal stream through the mould cavity heats it up. In consequence conditions of heat exchange along the flowing path are changing. Increasing distance from the inlet is accompanied by a shorter contact time of liquid metal with a mould, which increases the cooling rate. Cooling rate (see Table 1) in turn affects and increase the maximum undercooling at the onset of graphite eutectic. Maximum undercooling estimated from thermal analysis and from simulation are graphically shown in Fig. 6. The preheating during filling can has an influence to reduce \( D_{T_m} \).

Maximum undercooling obtained from simulation shows rather good conformity with experimental measurements. This is especially important because undercooling is the driving force measure for the nucleation stage during solidification. Not all substrates in the undercooled melt play an active role in the nucleation process. The minimum substrate sizes, which become active nucleation sites, decrease continually at increasing degrees of undercooling. In consequence nodule count increases. An influence of undercooling on eutectic nodule count estimated by metalographic examinations is show in Fig. 7.

Undercooling started from 48°C (at \( x = 0.01 \) m) and if distance from inlet increases it goes up to the value of 65°C. When maximum degree of undercooling increases, below the cementite eutectic formation temperature, chills can be formed in the structure. Below in Fig. 8 there are shown results of simulation both primary and eutectic graphite radii along with their austenite envelopes.

Calculated graphite radii can be compared with experimental. An average eutectic radius for \( x_m = 0.10 \) m amounts \( R_e = 3.42 \) \( \mu \)m (see Table 1). Simulation gives radius at the end of solidification amounted \( R_e = 2.75 \) \( \mu \)m. In case of primary graphite results are as follows: \( R_g (\text{exp.}) = 9.03 \) \( \mu \)m and \( R_g (\text{sim.}) = 6.12 \) \( \mu \)m. Simulation show a little lower radius in comparison to experimental results. The differences are connected with the effect of fluid flow, temperature drop and heating of the mould by flowing metal stream. The longer time of flowing metal stream the lower temperature drop and the lower cooling rate as a result of change in thermal parameters of a mould with temperature. In this connection fluid flow has an effect to the temperature distribution. Mainly it can be manifested by different slope of temperature–time curve before maximum undercooling (see Fig. 5). During fluid flow temperature can decreases below liquidus temperature for graphite. From this time flowing metal stream can have already nucleated primary graphite nodules, which growth in this period is not taken into account in numerical calculations. Moreover graphite keep growing even after the end of solidification, which is also not included in simulation. From these reasons simulated radii are understated.

It is worth to note that thin wall castings, which solidify with high cooling rate cause the melt undercooled below extrapolated liquidus line for austenite. As a result nucleation and growth of austenite dendrites takes place. Figure 9 presents undercooling below the extrapolated lines for austenite, which is the driving force measure for the solidification of austenite dendrites.

Influence of the solidification of austenite dendrite on cooling curve is pronounced and it is shown in Fig. 10. From Fig. 10 follows that nucleation and growth of austenite dendrites have an important thermal effect. It is visible by change in the slope on the cooling curve and also decreases in both undercooling and recalescence. In model-

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density of ductile iron, ( \rho )</td>
<td>7000</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Density of austenite, ( \rho_a )</td>
<td>7210</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Density of the mould, ( \rho_m )</td>
<td>1600</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Density of graphite, ( \rho_g )</td>
<td>2200</td>
<td>kg/m³</td>
</tr>
<tr>
<td>Specific heat capacity of ductile iron, ( c )</td>
<td>750</td>
<td>J/kgK</td>
</tr>
<tr>
<td>Specific heat capacity of mould material, ( c_m )</td>
<td>1200</td>
<td>J/kgK</td>
</tr>
<tr>
<td>Latent heat of graphite eutectic, ( \Delta H_a )</td>
<td>2.85 ( \times 10^4 )</td>
<td>J/kg</td>
</tr>
<tr>
<td>Latent heat of austenite, ( \Delta H_t )</td>
<td>2.6 ( \times 10^4 )</td>
<td>J/kg</td>
</tr>
<tr>
<td>Latent heat of graphite, ( \Delta H_g )</td>
<td>1.46 ( \times 10^4 )</td>
<td>J/kg</td>
</tr>
<tr>
<td>Gibbs-Thompson parameter, ( \Gamma )</td>
<td>1.9 ( \times 10^4 )</td>
<td>mK</td>
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<tr>
<td>Diffusion coefficient of carbon in liquid, ( D )</td>
<td>1.25 ( \times 10^{-9} )</td>
<td>m²/s</td>
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<tr>
<td>Diffusion coefficient of carbon in austenite, ( D_t )</td>
<td>1.2 ( \times 10^{-10} )</td>
<td>m²/s</td>
</tr>
<tr>
<td>Initial radius of nucleated graphite, nucleus ( R_n )</td>
<td>0.5 ( \times 10^{-3} )</td>
<td>m</td>
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<tr>
<td>Partition coefficient, ( k_p )</td>
<td>0.49</td>
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<tr>
<td>Thermal conductivity of mould material, ( k_m )</td>
<td>0.9</td>
<td>W/mK</td>
</tr>
<tr>
<td>Number of dendrites of austenite, ( N_d )</td>
<td>1 ( \times 10^{13} )</td>
<td>1/m³</td>
</tr>
<tr>
<td>Carbon content in austenite for ( T_e ), ( C_{e_1} )</td>
<td>2.08-0.11Si-0.35P</td>
<td>% wt.</td>
</tr>
<tr>
<td>Carbon content in eutectic, ( C_e )</td>
<td>4.26-0.30Si-0.36P</td>
<td>% wt.</td>
</tr>
<tr>
<td>Slope coefficient of lines ( m_1, m_2, m_3 ) – for E’S’, J’E’and 275°C/7% wt.</td>
<td>189.6</td>
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</tr>
<tr>
<td>BC’ in Fe-C-Si system</td>
<td>113.2</td>
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</tbody>
</table>

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ling of the solidification of ductile iron austenite dendrites should be taken into account. Especially in thin wall castings, because reducing wall thickness fraction of austenite dendrites increases. Such solidification behavior manifested by presence both primary graphite and austenite dendrites can be taken into account by numerical simulation.
given in this work. Moreover the database of experimental data in the form of thermal analysis and the metallographic investigation for different initial temperatures makes modeling of TWDI reliable.

Casting with the shape of Archimedes spiral is designed to the measure of fluidity. Aside from technological aspect in production TWDI (how is the fluidity of ductile iron for a given wall thickness) it represents different cooling conditions as the result of the fact that the metal flowing in the mould channel cavity heated it, and thus changing conditions for the exchange of heat flowing stream—the mould material. It has a pronounce effect on structure and in consequence on casting properties. Inhomogeneous of structure parameters can be observed. It usually applies to nodules count and to a smaller extent to the matrix. From work\textsuperscript{15} results that risers or multiply inlets can significantly reduce structure inhomogeneity.

6. Conclusions

(1) It has been adopted the model describing the solidification of ductile cast iron with hypereutectic composition in Matlab-Simulink environment. The model takes into account the presence of off-eutectic austenite as well as primary graphite. Both phases are typical for thin wall ductile iron castings.

(2) Experimental verification using casting with the shape of Archimedes spiral was done. Thermal analysis along with microstructure observations showed that cooling curves predicted with the presented model gives reasonable agreement with experimental measurements.

(3) Thermal analysis showed that there is high temperature drop of liquid metal due to intensive heat transfer between flowing metal stream—the mould material. Temperature drop can have a pronounce effect on structure and in consequence casting properties.

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