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Temperature drop of liquid iron in thin wall channels during mold filling

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Abstract

This work deals with first period of metal cooling in mold cavity. It has been performed thermal analysis of flooding metal stream in thin wall ductile iron with the shape of Archimedes spirals. It has been presented comparison of real temperature drop with predictions according to the analytical equations based on heat balance and with simulation using Fluent program. Additionally velocity decrease predicted by Fluent program is compared to the experimental data. Moreover change of cooling rate as function of spiral length of liquid metal before eutectic solidification is presented.

Key-words: The theoretical basis for casting processes, Ductile iron, Thermal analysis, Thin wall castings

1. Introduction

From literature it is known that it is plausible to produce lightweight and inexpensive thin wall ductile iron castings (TWDI). Possible application of TWDI include particularly automotive industries e.g. exhaust manifold, pumps and alternator parts, arms, wishbones, transmission housing, crankshaft bearing ladders, differential carrier, power steering and gear housing. Numerous studies have been published on thin wall ductile iron, particularly on the solidification morphologies[1], microstructural characterization[2-5], mechanical properties[6-11], carbide formation factors[12], production[13,14] and mold filling[15,16]. Moreover, various experimental relationships have been developed between the chemical composition[2,12,14], pouring temperature [9,16], spheroidization and inoculation practice [12,13,17], casting geometry[7], plate thickness [12,13,15], and mold materials [18]. Yet, most of these works are limited to simple plate shaped castings.

Metal flow during mold filling is undoubtedly an important process in the casting industry. Mold filling is the first stage (from pouring to solidus temperature) of metal cooling. The heat exchange in the metal-mold system is essential to the kinetics of cooling and solidifying of a casting. Especially in thin wall ductile iron (TWDI) castings which start to solidify during mold filling and which characterize high cooling rate. Examining and assessment of this stage (which influences casting structure and properties) of cooling and solidifying can be performed by thermal analysis [19,20] or by computer simulations methods [12-24]. Ductile iron is the material, which shows gradient character [4,5]. In works [4,5] it has been proved that pouring temperature (in mold represented by initial temperature of liquid metal) and also its further drop as a result of intensive heat transfer mold-flooding metal are responsible for gradient structure exhibited by variation in graphite nodule count, ferrite and cementite fractions in a cross section of a casting. In literature there are available analytical relationships (which are connected to the temperature profile) for critical distance from the beginning of ingate above which there are chills present in castings [4,25].

The aim of this work is to determine temperature drop in mold cavity and to compare it with calculations according to theoretical predictions and with computer simulation. With this end in view thermal analysis in thin wall castings with the shape of Archimedes spirals were made.

2. Experimental

In order to accomplish the aim of this work a special modeling lay-out was designed. Modeling lay-out consists of gating system and Archimedes spirals with 1500 mm length and 1x15, 2x15 and 3x15 mm sections, respectively. Common gating system enabled simultaneously filling spiral cavities with different wall thickness. Test melt was made in electric induction furnace. The raw materials were Sorelmetal, commercially pure silicon, and steel scrap. The metal was preheated at 1500 ^oC and then poured into the mold. Mold was made of chemically bounded silica sand. Spheroidization and inoculation processes were made in the mold, which were 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 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 mold cavity reproducing Archimedes spirals with 1500 mm length and different wall thickness. The chemical composition of the produced ductile irons was 3.64 % C; 2.94 % Si; 0.10 % Mn; 0.02 % P; 0.01 % S; and 0.03 % Mg.

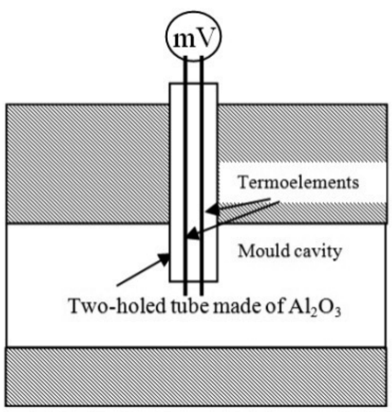

Fig.1. Measurement of temperature in mold cavity (b)

Temperature of metal in mold cavity with a shape of Archimedes spiral and with wall thickness of 3 mm was estimated using unsheathed thermoelements wires in regular 100 mm distances. Scheme of temperature measurement is shown in Fig. 1. 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. 2 it is shown castings of Archimedes spirals with wall thickness of 1, 2 and 3 mm.

Fig. 2. Photographs of Archimedes spirals with wall thickness of 1, 2 and 3mm

3. Results

In Fig. 3 there are presented cooling curves obtained at different distances from the beginning of spiral.

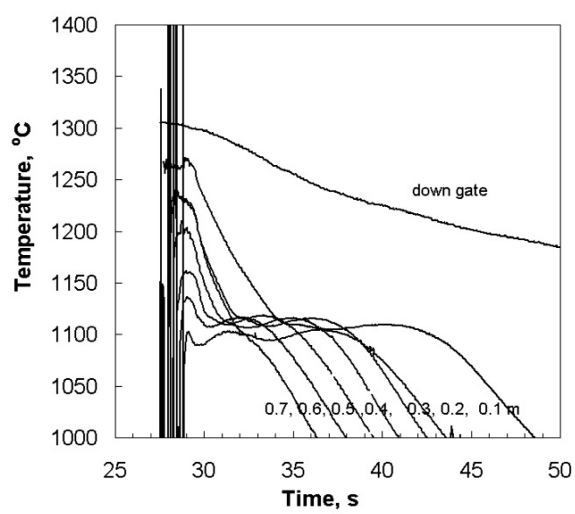

Fig. 3. Cooling curves of ductile iron recorded at different distance from the beginning of spiral

Fluidity distance versus time is estimated (Fig. 4) on the base of known distance between thermocouples and time of first signal recorded by thermocouple touched by flowing metal stream. Fluidity as a function of flowing time can be approximated by means of polynomial with correlation coefficient R = 0.99 in the form of:

$$L = 0.035156 + 0.929605t - 0.27697t^2 \quad [m] \qquad (1)$$

Metal stream velocity is the first derivative of fluidity (dx/dt) and from eq. (1) amount to:

$$v = 0.9296 - 0.554t \qquad [\mathrm{m\ s^{-1}}] \qquad (2)$$

Metal stream velocity changes linearly with time (Fig. 5). By combining eqs. (1) and (2) velocity can be presented as a function of fluidity length:

$$v = 1.05\sqrt{0.81 - L} \qquad [\mathrm{m\ s^{-1}}] \qquad (3)$$

Total fluidity length for spiral with 3 mm wall thickness amounts 0.86 m. The gathered data allowed to determine mean velocity of metal flow in a range L = 0 – 0.8 m. Dividing measuring flowing distance (L = 0.8 m) by flowing time (1.39 s) gives mean velocity of metal stream as 0.57 m s^{-1}.

From heat balance equation between heat lost by the flowing metal and gained by the mold, temperature of the metal in mold channel can be described by the following equations [26].

$$T_i = (T_p - T_o)\exp\left[-\frac{\alpha}{c\rho M}\left(\frac{Z}{v} - \frac{Z-x}{v}\right) + T_o\right], \qquad (4)$$

This equation assume moving coordinate system with origin at the metal front. This enable making the heat transfer coefficient formally the time-independent.

Heat transfer coefficient is given by the equation

$$\alpha = \frac{a}{\sqrt{\pi}}\sqrt{\frac{v}{Z-x}} \qquad (5)$$

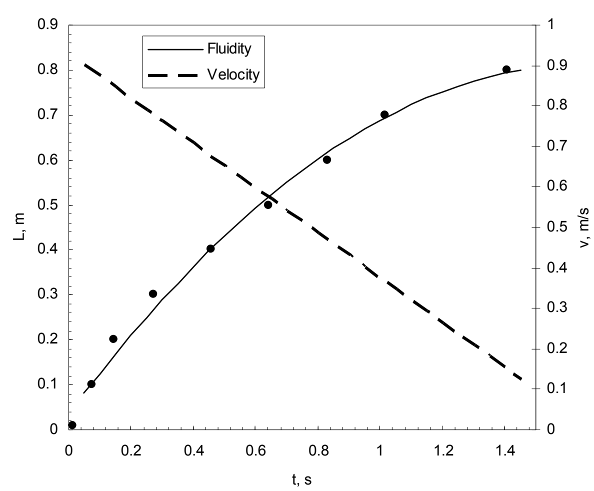

Fig. 4. Fluidity and velocity of metal in mold channel as a function of flowing time. Points represent experimental data

Taking into consideration eq. (5) temperature of the metal in mold channel can be rewritten in the form of:

$$T_i = (T_p - T_o)\exp\left[\frac{a}{cM\rho\sqrt{\pi}}\left(\frac{-x}{\sqrt{v(Z-x)}}\right)\right] + T_o \qquad (6)$$

The foregoing equations are valid on the assumption that: metal is flowing through channel with constant cross section and constant velocity (v) and heat is transferred in the direction perpendicular to the mold wall only. Temperature at the entrance to the mold channel amounts T_p, initial mold temperature amounts T_o and there is no solidification during mold filling.

In Eqs. (4) and (6) a is the material mold ability to absorb the heat, c is the specific heat, M is the casting modulus, ρ is the density of liquid metal, x is the distance from 0 to Z range and Z is the total fluidity (Fig. 5).

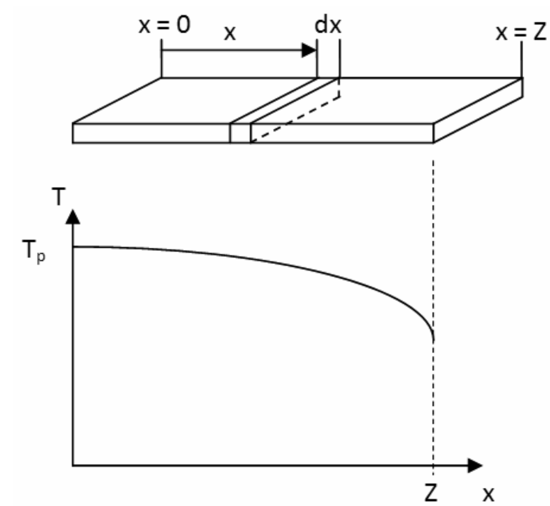

Fig. 5. Stream of liquid metal in mold channel and illustration of temperature decrease in mold channel

Mold filling simulations using Fluent program along with eqs. (4) and (6) will be verified experimentally.

4. Mold filling simulations

The simulations were carried out using Fluent™ program. It is a program which is widely used for computer fluid mechanics. Fluent uses a control-volume-based technique to convert the governing equations to algebraic equations that can be solved numerically. This control volume technique consists of integrating the governing equations about each control volume, yielding discrete equations that conserve each quantity on a control-volume basis.

Experimental data taken from thermal analysis are incorporated into calculations in Fluent program. Convective heat transfer boundary conditions are used for heat transfer coefficient at the metal stream/mold material interface amounts α = 1100 W m^{-2} K^{-1} . Temperature of liquid metal at the entrance to the spiral of 1306 °C was taken from thermal analysis. Initial velocity at the mold entrance is taken from equation (2) as 0.93 m s^{-1}. To describe turbulent behavior of flowing metal the k-ε model was applied. Thermophysical data used in simulation are given in Table 1.

Table 1. Thermophysical data used in simulation

Parameter	Unit	Value
Ductile iron		
Density [27]	kg m^{-3}	((T[K]=1298.15; ρ[kg m^{-3}] = 6953) (1328.15 ; 6940) (1388.15 ; 6914) (1439.15 ; 6877) (1442.15 ; 6512) (1448.15 ; 6458) (1454.15 ; 6452) (1460.15 ; 6446) (1466.15 ; 6441) (1472.15 ; 6435) (1478.15 ; 6430) (1484.15 ; 6424) (1490.15 ; 6419) (1496.15 ; 6413) (1502.15 ; 6408) (1508.15 ; 6402) (1511.15 ; 6400) (1517.15 ; 6394) (1520.15 ; 6391) (1526.15 ; 6386) (1532.15 ; 6380) (1538.15 ; 6376) (1572.15 ; 6352) (1632.15 ; 6310))
Specific heat	J kg^{-1} K^{-1}	800
Thermal conductivity	Wm^{-1} K^{-1}	22
Dynamic viscosity [27]	Pa s	(T [K] =1439.15 ; μ [Pa s]=0.0070) (1451.15 ; 0.0066) (1463.15 ; 0.0063) (1479.15 ; 0.0062) (1493.15 ; 0.0060) (1505.15 ; 0.0059) (1515.15 ; 0.0057) (1527.15 ; 0.0056) (1535.15 ; 0.0055) (1582.15 ; 0.0051) (1662.15 ; 0.0044) (1762.15 ; 0.0038))

Below in Fig. 6 it is presented real temperature drop of liquid metal in thin walled mold cavity along with predicted values according to eqs. (4), (6) and also predicted by Fluent simulation.

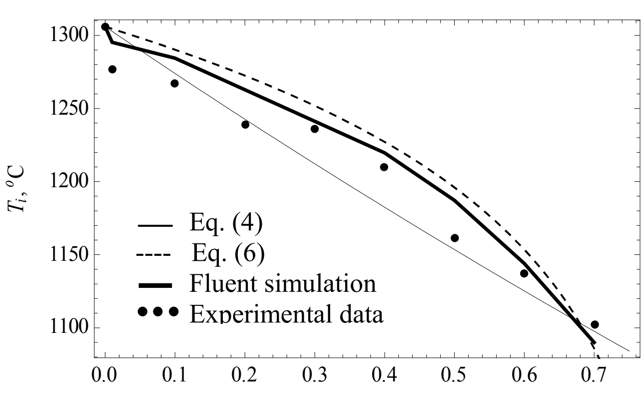

Fig. 6. Initial temperature of metal in mold cavity (T_i) during mold filling*.

*Calculations according to eqs. (4) and (6) were performed for the following data: T_p = 1306 ^{o}C; To = 20 ^{o}C; c = 800 J kg^{-1} K^{-1} ; M = 0.0015 m; a = 1100 W s$^{1/2}$ m^{-2} K^{-1}; α = 1100 W m^{-2} K^{-1}; v = 0.57 m s^{-1}; ρ = 6400 kg m^{-3}.

Statistical analysis show that mean absolute errors of temperature drop amount 13.3, 10.1 and 21.5 ^{o}C for Fluent, eq.(4) and eq. (6), respectively. The best matching is obtained for equation (4). Without professional numerical calculations by means of computer software rather good prediction of temperature drop can be achieve by relationship given by eq. (4). This equation gives similar result as simplified form proposed by Frederiksson [22] where temperature drop is given by linear equation:

$$T_i = \frac{T_o x\alpha + cMT_p v\rho}{x\alpha + cMv\rho} \quad (7)$$

Plot of eq. (7) along with experimental data and with prediction according to eq. (4) is presented in Fig. 7.

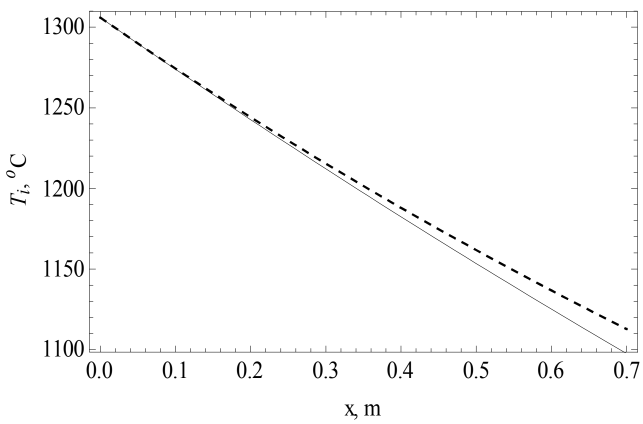

Fig. 7. Initial temperature of metal in mold cavity (T_i) during mold filling. Solid line - eq. (4), Dashed line – eq. (7)

From statistical analysis result that for eq. (7) absolute error of temperature drop amounts 10.2 ^{o}C. It is almost the same result as for eq. (4). It means that without extensive numerical calculations temperature drop can be estimated with relatively high accuracy by means of analytical equations resulted from heat balance between heat lost by the flowing metal and gained by the mold.

Fluent program takes into account thermophisical parameters as a function of temperature, change in velocity during mold filling, wall roughness as well as turbulent behavior of liquid metal. From a viewpoint of velocity of metal stream eqs. (4,6 and 7) uses its mean value. Thus it is necessarily to have credible data concerning flowing time and castability. In contrary Fluent program uses only initial velocity at the entrance to the mold cavity. As a result of heat transfer profile of velocity of metal stream can be obtained. Another crucial parameters is the heat transfer coefficient and material mold ability to absorb the heat. Heat transfer coefficient between metal stream and mold material for thin wall castings made of ductile iron flowing through channel made of silica sand usually is set [29] at the level of 1000 W m^{-2} K^{-1}. It represent insulation properties of the mold and which is main controlling factor in the solidification/heat transfer of sand casting. In this work better fitting to the experimental data was obtained using 1100 W m^2 K^{-1}. Eq. (6) shows a bit higher mean absolute error in comparison to eqs. (4), (7) and Fluent simulation. Nevertheless temperature profile is consistent to Fluent simulation. Both eq. (4) and fluent simulation exhibit temperature drop as of parabolic – concave function of fluidity length. In eq. (6) material mold ability to absorb the heat instead of heat transfer coefficient is taken into account. In this case calculations were made for value of 1100 W $s^{1/2}$ m^{-2} K^{-1}. Nevertheless, from literature [28] it is known that this thermophysical parameter for a given mold materials depends among other things on temperature. Precise measurements of this parameter for a given metal-mold system can result in better fitting experimental results with theoretical predictions.

In Fig. 8 it is presented extrapolated velocity profile according to eq. (3) along with simulation according to Fluent program.

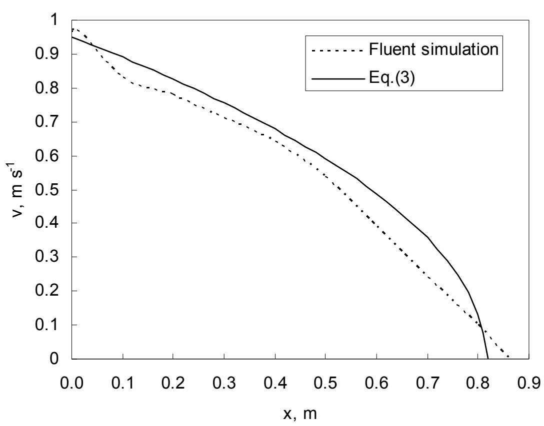

Fig. 8. Velocity of metal stream in mold channel

The metal flow is accompanied by intensive cooling at the mold walls. This result in velocity decrease. Fluent predictions show fairly good matching, with mean absolute error amounted 0.05 m s^{-1} to an extrapolated velocity profile according to eq. (3).

Temperature and velocity drop have an effect on heat exchange rate and in consequence on cooling rate. In Fig. 9 it is presented cooling rate estimated (near eutectic equilibrium temperature) from thermal analysis as a function of distance from the mold cavity entrance.

Cooling rate has influence on solidification conditions. The higher cooling rate the higher degree of undercooling at the beginning of eutectic solidification. This lead to increase in graphite nodule count and decrease in ferrite fraction. Flowing metal stream can exceed critical distance at which cooling rate can be high enough to reach conditions to chills formation. Such gradient structure can result in inhomogeneous mechanical properties. In order to produce thin wall ductile iron castings with homogeneous structure a few ingates are recommended in gating system design.

5. Conclusions

Thermal analysis show profile of temperature and velocity drop during mold filling. High temperature drop result in increase in cooling rate of liquid ductile iron (before eutectic solidification) as function of spiral length. Due to intensive heat transfer at the mold-flooding metal interface during mold filling any solidification simulation of thin wall ductile iron that neglect this stage has little practical value. Thermal analysis of flowing metal stream can be exploit to determine parameters connected with the first period of metal cooling in mold cavity and thus provide an experimental data which can be used in computer simulations.

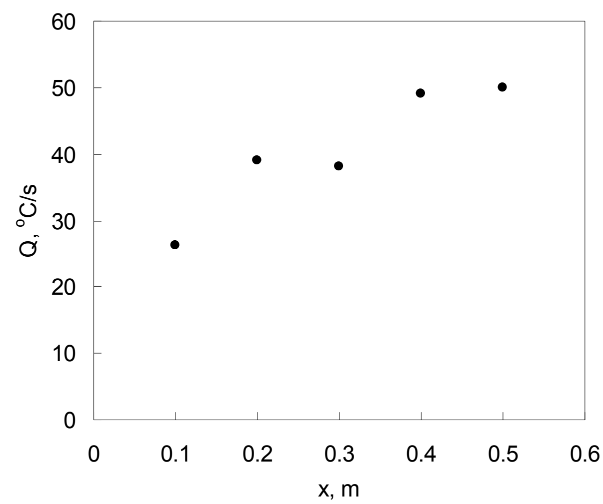

Fig. 9. Cooling rate as a function of flowing distance

Calculations of temperature drop according to analytical equations based on heat balance (eqs. (4) and (6) and (7)) show that there is fairly good correlations with experimental data. Both analytical equation (eq. (4)) and Fluent simulation exhibit temperature decrease as of parabolic – concave function of fluidity length.

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