Identification of temperature changes dynamics in selected castings as a contribution to performance life improvement

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Abstract

Parameters describing boundary conditions and dynamics of temperature changes during casting cooling in foundry moulds and the successive performance, especially as regards the massive cast elements, were discussed. Considering the specific nature of casting operation, non-standard methods of examination of the isotherms of temperature fields on the casting surface were described to determine local overheating resulting from the technological process, chemical composition, properties of the currently applied insulation materials, casting defects and/or design. Identification of these parameters can be interpolated to laboratory conditions and to the validation of virtual models subject to computer simulation. The use in simulation of genetic algorithms combined with the results of measurements under real conditions enables more precise determination of the performance parameters, including critical states of stresses present in a structure. This should allow further optimisation of the massive castings design, considering the specific nature of a manufacturing process (alloy composition included), combined with performance parameters. Measures described here are expected to contribute to the reduced casting weight and longer time of operation.

Keywords: grey cast iron, vermicular graphite cast iron, cast plates, casting life, computer simulation, thermal fatigue

1. Introduction

This paper is the first in a planned series of publications that will appear in print in the course of the research tasks executed under the project „Research and development of modern technology for cast materials resistant to thermal fatigue” included in the Operational Programme Innovative Economy in years 2007-2013. The problem of the thermal fatigue of materials operating under the conditions of cyclic temperature changes occurs in numerous key sectors of the industry. Castings used in automotive industry (heads, cylinder sleeves, manifolds), metallurgical industry, and glass industry can suffer total destruction due to the effect of stresses formed during their operation. Numerous enterprises use in the technological processes the devices operating under the conditions of cyclic temperature changes. Recently, in some of these sectors (e.g. copper metallurgy), the production volume has increased several times, mainly due to the improved output of a technological process, but cast materials for parts of machines and equipment have not changed since early seventies of the past century, and as such cannot meet the requirements of modern technology. Cast dies, die bottom plates, anode moulds, pouring ladles,
furnaces, caissons, etc. operating under the conditions of thermal shocks and dynamic loads suffer destruction and require complete replacement in a time much shorter than the planned operating period. In many cases, the cost of making cast parts of machines and equipment and of the current repair amounts to tens of thousands of the Polish zlotys, while the operating period is reduced in respect of the planned time from years to months. Analysis of selected literature [1-4] shows that how to improve the fatigue resistance of materials is important all the time. Increasing the performance life of moulds depends, among others, on the choice of material which should be characterised by the following parameters [3, 5-7]:

- high mechanical properties,
- high abrasion wear resistance,
- homogeneous structure,
- resistance to oxidation and thermal shocks,
- high thermal conductivity,
- low coefficient of thermal expansion,
- swelling resistance,
- possibly low manufacturing cost.

It seems that the development of a material that would meet so complex criteria and could satisfy the most challenging conditions of casting performance requires non-standard approach to the problem of performance life improvement, the essence of which consists in preliminary identification of the most important parameters describing the boundary conditions and dynamics of temperature changes within the examined group of castings.

2. Identification of boundary parameters in cast massive plates and description of studies

Investigations were carried out on two die bottom plates of 4100 kg weight each cast from grey iron and vermicular graphite iron, assigned for further casting of copper dies. Cast iron was melted in a 6000 kg capacity electric arc furnace with basic lining. The metal was tapped to stopper ladles, also with basic lining. During tests, oxygen activity was measured with Multi-Lab apparatus in molten iron after the vermicularising treatment to examine the shape of graphite (nodular, vermicular, flake). The vermicularising treatment was carried out with magnesium master alloy of the following chemical composition (wt.%): Si=44-48, Mg=5-6, RE=5,50-6,50, Ca=1,8-2,3, Al max. 1,0, placed together with inoculant on the bottom of a ladle. The content of master alloy was calculated so as to obtain the final magnesium content in cast iron in a range of 0,01-0,025%. The inoculant was added in an amount of 0,75% in respect of the metal weight. The oxygen activity $a_o$ measured in cast iron subjected to vermicularising treatment was 142,45 and 137,60 ppb and indicated that the obtained values were comprised in a range proper for the manufactured grade of the vermicular graphite cast iron GJV (140-300 ppb). The main data, i.e. the tapping temperature and pouring temperature, were measured with immersion thermocouple, while cast iron temperature inside mould was measured in a continuous manner for the time of about 20 hours using thermocouple connected to a recording unit. The data from the measurements are compared in Table 1. Table 2 gives chemical composition of the manufactured cast iron.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Cast iron temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Casting cooling time, h</td>
</tr>
<tr>
<td>Tapping temp.</td>
<td>1320</td>
</tr>
<tr>
<td>Pouring temp.</td>
<td>1260</td>
</tr>
<tr>
<td>Temp. in mould axis</td>
<td>1220</td>
</tr>
</tbody>
</table>

Table 1. Temperature parameters of cast iron

<table>
<thead>
<tr>
<th>Cast iron grade/ study location</th>
<th>Chemical composition, wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>Grey/foundry shop</td>
<td>3.75</td>
</tr>
<tr>
<td>Vermicular/ foundry shop</td>
<td>3.73</td>
</tr>
<tr>
<td>Vermicular/ Institute</td>
<td>3.75</td>
</tr>
</tbody>
</table>

Table 2. Chemical composition of cast iron

Mechanical tests carried out on cast iron grade EN-GJL250 in the form of separately cast rods confirmed the required tensile strength of this material (about 250 MPa – pearlitic structure). Mechanical tests carried out on sample plates machined (turning) from the separately cast test ingots of 40 mm wall thicknesses after the vermicularising treatment revealed the following values: tensile strength of 480 MPa, hardness of 200 HBW and elongation $A_5=5\%$ (for a ferritic-pearlitic structure).

Figure 1 shows photograph of cast iron structure (unetched specimen) obtained in a test melt carried out under laboratory conditions at the Foundry Research Institute in Cracow (Y2 test ingot), vermicularised with the same master alloy before testing. The chemical composition was similar to the composition of cast iron plate.

Figure 2 shows photograph of the structure of graphite precipitates in an iron specimen cast-on to the plate side.
The appearance of graphite precipitates in cast iron after the vermicularising treatment carried out under laboratory conditions (Y2 ingot - Fig. 1) and in industry (cast-on specimen – Fig. 2) is different although in both cases the tensile strength \( R_m \) of the cast iron plate is high \( (R_m=480 \text{ MPa}) \).

The chemical composition of cast iron made at the Foundry Research Institute was examined by the method of emission spectrometry on an ARL spectrometer; the photographs of graphite structure were taken on an Axio Observer Z1m light microscope.

3. Numerical analysis of the casting process and die bottom plate operation

The numerical analysis of the casting process was carried out on parts cast from grey and vermicular graphite irons. MAGMAIron programme was used. It enables predicting the final properties of castings based on preset boundary parameters. The MAGMAIron module uses kinetic model of microstructure growth and formation, which allows for local changes of alloy properties, including thermo-physical changes, especially at the solidification front boundary, due to the segregation of elements. It also allows for other factors, like alloy composition, inoculation method, solid state phase transformations, silicon content effect on the segregation phenomena, and effect of basic alloying elements on the solidification process.

The numerical calculations made for the cast die bottom plate (Fig. 3) aimed at the determination of the characteristic final properties of casting, allowing also for the cast iron type (grey/vermicular).

The temperature distributions plotted within the area of eutectic transformation (Fig. 4) show us that the inoculating elements, magnesium in this case, introduced to alloy result in a strong undercooling effect. The vermicular graphite cast iron is solidifying at a lower temperature and higher undercooling than the cast iron with flake graphite. For grey cast iron, the
temperature drop below an equilibrium temperature amounts to several degrees only, while for the cast iron with an addition of magnesium the undercooling is 20°C. For the solidification process to start, the free energy of the system must drop. Large undercooling is more powerful in reducing the free energy; it also reduces spacing between the short-range ordered groups of atoms of the liquid phase, which act as nuclei of the homogeneous crystallisation.

Fig. 4. Plotted diagrams of temperature distribution within the range of eutectic transformation for composition 1 (left) and 2 (right)

The solidification process causes increase of temperature (recalescence) with simultaneous crystallisation of graphite and austenite. The rapid decrease of the system free energy (large undercooling) favours the formation of graphite characterised by compact structure and less sharp edges compared to the flake graphite in grey iron; nodular graphite appears as well. A measure of the nodular graphite content in vermicular graphite cast iron is the nodularity value expressed in percent. The numerical analysis
of the examined composition of the vermicular graphite cast iron shown in Table 2 has indicated the nodularity of about 24 %, as shown in Figure 5.

Fig. 5. The value of nodularity in vermicular graphite cast iron used for die bottom plate

In vermicular graphite cast iron, the shape and form of graphite determine final properties of this material. The branched structure of graphite without any sharp edges increases the cast matrix strength [8–9]. Figures 7 and 8 show pearlite content and final strength values in the cast plate of composition 1 and 2. For similar mean content of pearlite in the structure amounting to about 40 %, the tensile strength of the casting made from grey iron is 180 MPa (Fig. 7), while for the vermicular graphite cast iron it reaches the level of 360 MPa (Fig. 8). So high increase of strength is mainly due to the effect of graphite shape that occurs in vermicular graphite cast iron. In a similar way, an increase in the Young’s modulus value shown in Figure 9 is the result of graphite shape, different in both cast iron grades. The deep-etched matrix with a 3D image of graphite, shown in respective photographs (Fig. 6), enables us to understand how important role the graphite plays, especially as regards the effect of its shape on cast iron properties. In the case of vermicular graphite cast iron, the surface is very irregular with rounded edges, “embracing” with its curvatures and ramifications all possible details of the cast iron matrix (ferritic-pearlitic).

Fig. 6. Graphite morphology in grey and vermicular cast irons (1000x in original) [8]

Fig. 7. Pearlite content (%) and tensile strength $R_m$ (MPa) of grey cast iron die bottom plate (mean values are given in frames)
Fig. 8. Pearlite content (%) and tensile strength $R_m$ (MPa) of vermicular graphite cast iron die bottom plate (mean values are given in frames)

Fig. 9. Young’s modulus (GPa) calculated for various plate materials (grey iron – left, vermicular graphite iron – right; mean values are given in frames)

Fig. 10. The design of cast iron die for pouring of copper dies and temperature distribution on pouring
Obviously, the energy necessary to initiate the destruction of such matrix must be greater than the energy necessary for the destruction of a matrix deprived of the strong bonds, e.g., a matrix of the type as occurs in grey iron. Therefore, for the same content of pearlite, the tensile strength shown in Figure 8 will be higher in the plate cast from the vermicular graphite iron than in the plate cast from grey iron (Fig. 7).

Operating as parts of the equipment for casting of copper dies, the cast die bottom plates are exposed to the effect of the variable fields of temperature. The process of die filling usually takes the time of about 360 seconds (Fig. 10). After the period of solidification and cooling, i.e., after the time of 120 to 180 minutes, the sides of the cast iron die are raised.

Figure 11 shows temperature distribution in selected places of the die bottom plate. Curve no. 2 shows temperature distribution in the centre of plate at a distance of about 15 mm from its upper surface, while curve no. 5 shows this distribution in the end part of the plate. Within the time of about 30 minutes since the end of pouring, the temperature in the cast iron die reaches its maximum value.

In a similar way, the difference of temperatures at the individual measuring points is during this time the greatest and amounts to nearly 200°C. This distribution of temperature generates stresses. Figure 12 shows stress distribution in the direction of Y axis and deformation (in enlargement) at the 76th minute since the end of pouring. During this time, the upper part of the plate is subjected to the effect of tensile stresses (Fig. 13), reaching in this area an average value of about 140 MPa, while in the lower part of plate the stresses are of a compressive character. After the lapse of 3 hours, the temperature acquires a uniform distribution (Fig. 11) and the plate assumes its original shape. In grey cast iron plate with an average tensile strength of 180 MPa (Fig. 7), the operation under the conditions of cyclic temperature changes results in premature wear, while the performance life of a plate made from the vermicular graphite cast iron with the tensile strength of 360 MPa (Fig. 8) will be much longer.

The numerical analysis of the casting pouring process and of its later operation under the challenging conditions of temperature fields changing in cycles has proved that the performance life of elements and the time of their operation can be considerably improved when the cast iron with vermicular graphite is used.

4. Discussion of results and conclusions

- Preliminary trials were carried out on cast die bottom plates of a weight of about 4100 kg using grey iron subjected to the vermicularising treatment.
- Identification tests of the boundary parameters of the technological process were carried out in foundry; the tests included: plate pouring temperature, the dynamics of temperature changes in foundry mould during casting cooling, chemical composition including active oxygen content level, the structure and mechanical properties of cast iron.
- Identification and analysis of real casting parameters, i.e. process temperature, including the dynamics of temperature
changes during casting cooling, chemical composition, cast iron structure, mechanical properties and other parameters, also in castings during operation, are necessary for correct computer simulation performed on selected group of castings.

- Casting simulation performed on plates made from both grey and vermicular graphite irons has proved that with similar pearlite content in the structure of both castings, the tensile strength of plates cast from the vermicular graphite iron has increased by 100 %. Also Young’s modulus has increased from 117 GPa to 160 GPa, which should have a beneficial effect on casting performance parameters when subjected to the cyclic changes of shape. During operation of die bottom plates, the maximum tensile stresses assume an average value of 140 MPa. For grey iron plates, this is 80% of the maximum admissible loading, while in the case of vermicular graphite cast iron it is 40% only. The numerical analysis of the pouring process and casting operation under the most challenging conditions of temperature fields changing in cycles has proved that life of parts and time of their operation can be considerably improved using the vermicular graphite cast iron.

- The trial industrial operation of plates cast from the vermicular graphite iron without detailed study and analysis of actual parameters has shown the life of these plates by about 40% longer than the life of plates cast from grey iron.

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References