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Effect of Inoculants on the Structure and Properties of Thin-Walled Ductile Iron Castings

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Abstract

In many application fields, thin-walled ductile iron castings can compete with castings made from aluminium alloys thanks as their show superior mechanical properties higher stiffness, vibrations damping as well as properties at higher temperatures. As problematic criterion in thin-walled cast-iron castings can be seen the graphitization ability and high sensitivity of the structure and the mechanical properties to the solidification rate.

The tests were curried on plate castings with wall thicknesses of 3, 5, and 8 mm, using inoculants based on FeSi70 with different contents of nucleation-active elements as aluminium, calcium, zirconium and magnesium. The inoculation was made by the in-mould method. In the experiments structures were achieved, differing by the graphite dispersity, structure and mechanical properties.

The experiments have proved particularly a high sensitivity of the structure and the mechanical properties to the cooling rate of the sample castings. The influence of the inoculant type is less important than the influence of solidification rate.

Keywords: Thin-wall castings, Ductile iron, Inoculation, Structure, Mechanical properties

1. Introduction

The very good mechanical properties of ductile cast iron (DI) make it possible to achieve the required strength of the castings with the walls being substantially thinner than those in lamellar graphite castings. The wall thicknesses of some products may be reduced down to a few millimetres so that, thanks to the higher specific strength, their weights may compete with the aluminium castings. In addition to good mechanical properties, the ductile cast iron's strength at high-temperature and vibration damping are better than those of the aluminium cast alloys.

As thin-wall ductile irons (TWDI) are usual considered castings with a wall thickness of less than 5 mm [1], other authors limit the thickness to be less than 3 mm [2, 3]. A value of 1 mm is taken to be the least realistically applicable thickness of TWDI castings [4].

Compared with castings of usual wall thicknesses, casting with such thin walls brings some new problems as well:

- The running property of metal in thin walls being lower, the length of the metal flow in the mould is limited,
- The metal solidification at a higher cooling rate increases the tendency towards metastable structure thus substantially influencing the metal structure and the dispersity of the structural constituents,
- High precision of the mould is required, particularly concerning its wall thickness because even relatively small thickness differences may radically influence the metal crystallization in thin-walled castings.

The cooling rate of castings in moulds depends mainly on the thermophysical properties of the sand mixture, usually expressed by the heat accumulation coefficient b_f.

As the differences between the values of b_f usual for sand mixtures are not very large, they cannot be used to achieve cooling intensity changes of some technical importance. For this reason, the possibility is considered of using moulding materials with a substantially lower cooling property denoted as Low Density Alumina Silicon Ceramic (LDASC) – [5, 6]. Results indicate that its use makes it possible to significantly increase the running property of the metal in moulds as well as the graphitizing ability of the cast iron and the ferrite/perlite proportion. Using LDASC for a standard application also bring some economic and technological problems, however. A technically easier way of producing TWDI seems to be a metallurgic control of crystallization by combining the choice of the chemical composition of the cast iron with the choice of suitable graphitizing inoculation agents.

1.1. Nucleation and graphite growth in ductile cast iron

In thin-walled ductile iron castings, the graphite nucleation is a major metallurgic problem. Graphite crystallizes on nuclei, mainly composed of sulphides, oxides, or nitrides of elements with a low value of enthalpy ΔG and high stability at high temperatures. A necessary condition is also good crystalline compatibility of the nuclei with graphite as well as a high surface tension between the nuclei and the liquid metal [7]. Crystallization is significantly influenced by the presence of a number of elements in the iron in quantities usually less than 0.1 %, termed as crystallizing active elements. Elements supporting graphite nucleation are mainly – Al, Ba, Ca, Ce, La, N, S, Sr, Zr. An analysis of the crystallizing nuclei [8] has confirmed that most of the germs of nuclei is formed by various complex components containing sulphides, oxides, nitrides, and silicates. Sulphides of Mg and oxisulphides Mg-Ca prevail. In some case germs of nuclei were detected based on carbides or carbonitrides [9-11], A two-phase graphite nucleation may also occur with the germ nucleus being formed by the Mg-Ca sulphides on which the envelope crystallizes of the $MgO.SiO_2$ and $2MgO.SiO_2$ silicates or aluminium oxides as well in the form of complex $MgO.Al_2O_3$ or $MgO.Al_2O_3.SiO_2$ compounds

Analyzing the graphite nuclei, Lekakh [12] found that the germs of nuclei are formed by MgO oxides and complex Mg_2SiO_4 a $Ca_3MgSi_2O_8$ oxides. The CaO, SrO or BaO oxides may also be contained in complex oxides. The germs of nuclei may also be formed by nitrides of the (MgSiAl)N type [13, 14]. The size of the crystallizing germs is 1-3 μm.

Generally, the nucleation mechanisms analyzed confirm the important role the crystallizing active elements by solidification of ductile iron particularly under conditions of problematic graphitization, which usually accompany present when thin-walled castings are made.

1.2. Chemical composition and test pieces of TWDI castings

To prevent the formation of free carbides by solidification of thin-walled DI castings, overeutectic chemical composition must be chosen with a high value of the CE carbon equivalent, a low content of the residual magnesium and antigraphitizing elements. Referring to Henning, Stefanescu [15] recommends calculating CE for wall thickness of t ≤ 3 mm by the equation

$$CE = 4.9265 - 0.0425 \times t \qquad (1)$$

where t is the casting wall thickness [mm]

Javaid [16] recommends a more generally applicable range of the cast iron composition for thin-walled castings $3.65 - 3.95\%$ C, $2.4 - 3.4\%$ Si, $0.03 - 0.045\%$ Mg, $0.005 - 0.01\%$ Ce and $< 0.1\%$ Mn while keeping high the proportion of quality pig iron in the charge with a low content of accompanying elements.

To test the structure and properties of thin-walled castings several castings are used in the form of plates or rods usually 1 to 5 mm thick cast individually on a common gate system or castings with gradually increasing thickness. The castings are cast in horizontal ore in vertical position – Fig. 1. The horizontal setup is technologically easier than the vertical one, however, Labresque [4] reports that it sometimes causes axial shrinkages because of the insufficient metal feeding during solidification. This was also confirmed by the experiments we carried out.

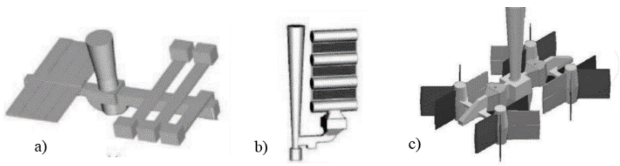

Fig. 1. Test pieces a),b) by Stefanescu, c) by Labresque [4, 15]

2. Experimental testing of inoculation

2.1. Experiments arrangement

The experimental testing aimed to verify the graphitizing effect of 6 different FeSi70/based inoculants, and their influence on the structure and on the mechanical properties of tin-walled castings.

The test castings had the shape of flat plates sized 180 by 60 mm thick 3, 5, and 8 mm. The three bodies were placed on a common gating system, Fig. 2. The moulds were made by self-hardening Geopol mixture. Cast metal weight in one mould is about 7 kg.

The cast iron was melted in an induction furnace and modified by the Tundish method by the Elkem modifiers Lamet and Topseed without any inoculants. The weight of melt is about 60 kg and 6 moulds were cast by each melt.

A total of 6 melts were made denoted A - F with a very similar final chemical composition in the interval 3.6-3.7 %C, 2.6-3.2 %Si, 0.15-0.25 %Mn, 0.03 %P, and 0.035-0.05 %Mg, carbon equivalent CE in the interval 4.55-4.7. The aim of A-D melts was to prove the inoculation effect and function of the gating system. The casting properties were tested only on E and F melts. Chemical composition of the tested iron E and F and casting temperatures are listed in Tab. 1

Table 1.
Chemical composition after modification and start pouring temperatures of E and F melts

Melt	C %	Si %	Mn %	P %	S %	Mg %	CE	Pouring Temperature [°C]
E	3.66	3.15	0.15	0.03	0.012	0.037	4.71	1408
F	3.70	2.64	0.27	0.01	0.017	0.033	4.58	1440

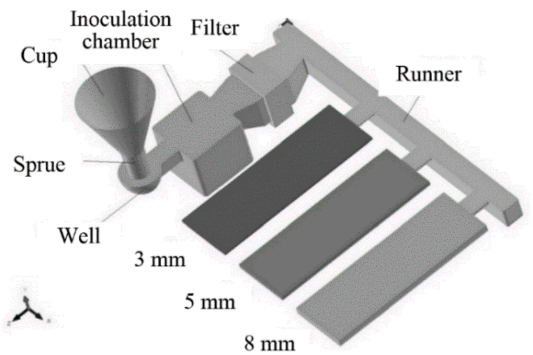

Fig. 2. Scheme of the experimental castings

Inoculation was made by In-mould method by inoculant inserts placed into inoculation chamber. All the inoculants are the FeSi70 type and differ from content of nucleation active elements aluminium, calcium and zirconium, one of them by higher manganese content. The weight of inoculation bodies was 10 g each which corresponds to the dosage 0.15 % of the metal cast weight. The chemical composition of inoculants is given in Table 2.

Table 2.
Chemical composition of inoculants

Inoculant	Si (%)	Mg (%)	Al (%)	Ca (%)	Mn (%)	Zr (%)
1	71	1,5	4	1,3		
2	71	2,1	0,9	0,9		1,8
3	68	1,1	3,4	1		
4	68	1	3,7	1,1		1,6
5	65	1,1	1	1,2	4	3,8
6	72	0,7	0,4	0,3		

On the test castings the internal homogeneity, the morphology of graphite, the metal structure, the mechanical properties, the hardness and, in a limited scope, the tensile strength and the ductility were analysed.

2.2. Internal homogeneity of test castings

All the test castings were completely filled with metal, no misrun ore chill has occurred. An X-ray analysis has stated, in all cases, presence of the axial-shrinkage type defects in central parts of castings, Fig. 3. Dotted line shows the typical defect region.

The shrinkages are caused by non-directed solidification of metal in the central parts of castings without any possibility to supply the metal from the gate and out of the reach of the cooling influence of the peripheral walls. The dimensions of the castings exceed the metal feeding capability in this case and give rise to axial shrinkages, which cannot be eliminated by a gate system or any side-risers. Even if the composition of the cast iron E and F was rather overeutectic, the capability of graphitic expansion during solidification to eliminate shrinkages is not sufficient. The area of internal shrinkages in castings of a small thickness of 3 mm, is larger, than in castings thick 5 and 8 mm, in which the shrinkages are concentrated in a narrower area around the thermal axis.

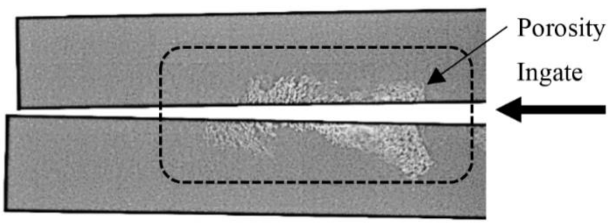

Fig. 3. X-ray image of an internal shrinkage in a casting thick 3 mm

In Fig. 4 the micro-shrinkages layout is shown in the transversal section. On a detail displayed in Fig. 5 it is evident, that the graphite expansion doesn´t compensate he metal shrinkage. Occurrence of these internal defects, particularly in horizontally positioned walls, complies with the prediction by Labresque [5] and their presence might be expected in real thin-walled castings.


Fig. 4. Axial shrinkage in a casting 3 mm thick

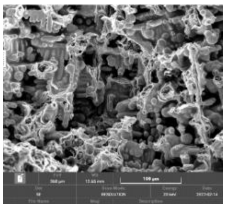
Fig. 5. Detail of a micro-shrinkage

2.3. Structure of test casting

Graphite

The structure of iron was investigated by optical microscopy at a distance of 20 mm from the ingate. The morphology of the graphitic phase of the castings from melt F was evaluated by mean of image analysis by EN ISO 945-1 standard too.

Typical example of the graphite structure in the test castings 3, 5, and 8 mm thick is shown on fig. 6.

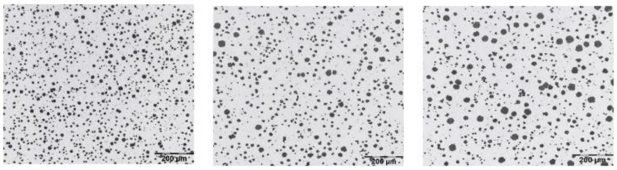
Fig. 6. Graphite in samples thick 3, 5, and 8 mm

All the test castings show high sensitivity of the graphite size and graphite dispersity to the casting thickness.

Fig. 7 shows the graphite size evaluated by melt F, inoculant F4 as a typical case. It is evident that, in castings 3 mm thick, graphite tends to be of size 8 and, as the thickness of a casting grows, the proportion of sizes 7 and 6 increases. The finest graphite is achieved with inoculants Nr. 2, 4, and 5 containing Zr. By these inoculants, the graphite getting coarser tendency to the increasing thickness of the casting walls is lowest of all.

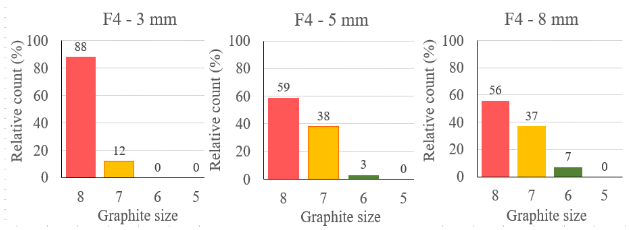

Fig. 7. Graphite size in castings from melt F

The graphite dispersity, defined as the number of graphite particles on a surface of 1 mm^2, depends particularly on the thickness of casting walls as well – Fig. 8. The graphite dispersity shows major dependence on the wall thickness particularly in thin walls castings. Influence of inoculant type is less significant as obvious on Fig.9.

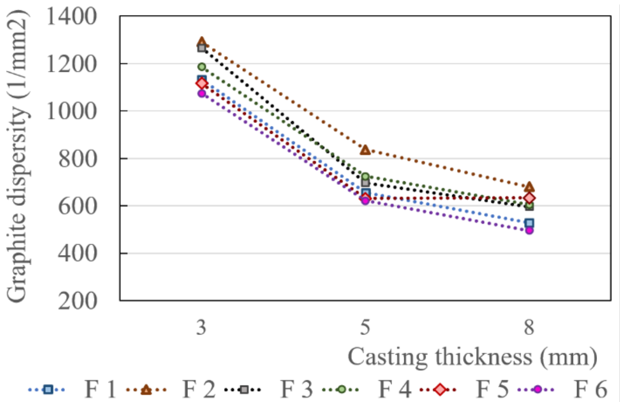

Fig. 8. Graphite dispersity depending on the casting wall thicknesses

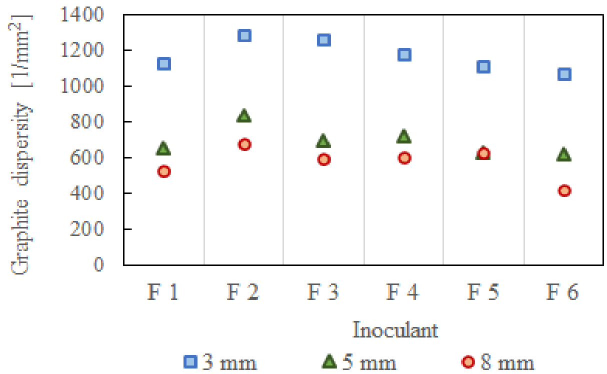

Fig. 9. Influence of the inoculants on the graphite dispersity

Metal structure

In all test samples, the metal structure is ferrite-pearlitic, no occurrence of a cementite was detected. Figure 10 shows the typical structures in etched state of 3, 5, and 8 mm thick plates. With the growing wall thickness, in all cases, the proportion of ferrite increases significantly – Fig. 11. The influence of the inoculant type is of less importance than of the casting thickness.

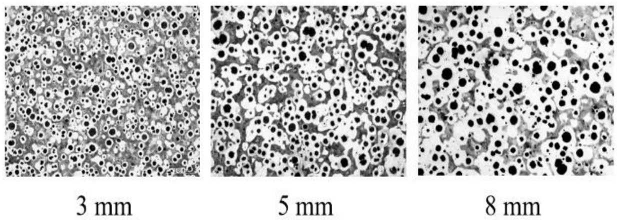

Fig. 10. Structure of 3, 5 and 8 mm thick castings

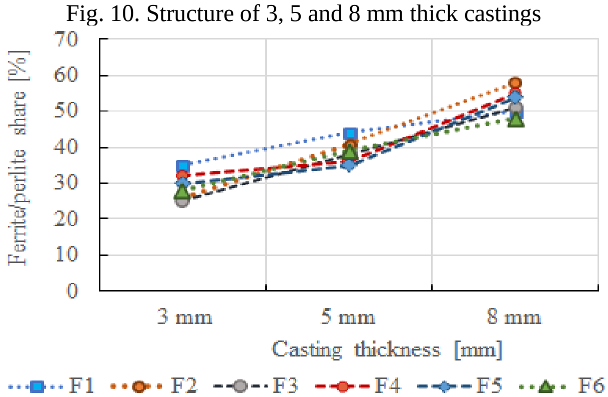

Fig. 11. Ferrite/pearlite proportion in the structure

2.4. Mechanical properties

In castings of all melts, the hardness was measured. By castings from melt E the tensile strength and ductility were evaluated as well using flat samples according to the ČSN EN ISO 6892-1 standard.

Hardness

The hardness as HBW 5/750 was measured at a distance of 15 mm from the lateral sides along of the castings. The dependence of the hardness on the wall thickness indicates enormous sensitivity to the cooling rate, represented by the thickness of the casting wall - Fig. 12. The influence of the inoculant type on the hardness is less significant - Fig. 13. The hardness dependency by melts E and F are very similar.

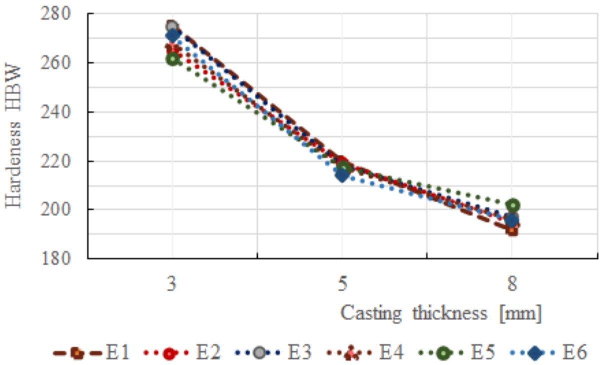

Fig. 12. Influence of the casting wall thickness and inoculant type on hardness

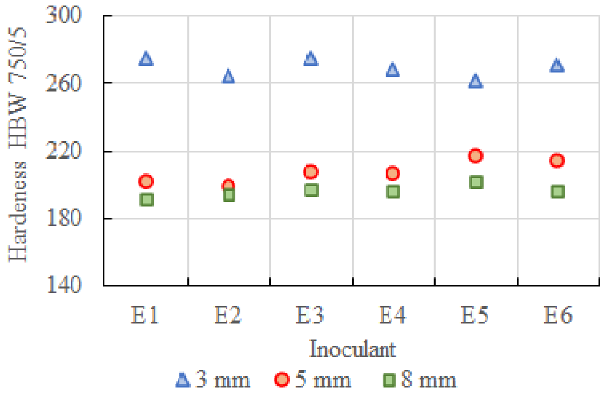

Fig. 13. Relation of hardness on the inoculant type

Strength characteristics

Flat sample from melt E were used to carry out tensile R_m and ductility A_{40} tests of the castings. For each of the castings, measurements were carried out on 2 specimens taken from areas outside the predicted micro-shrinkage regions. The dependence of tensile strength on the thickness is shown in Fig. 14, that on the ductility in Fig. 15 As in hardness, in the strength, too, a significant influence of the wall thickness, particularly in very thin-walled castings can be observed. The strength in the samples with a thickness of 5 mm is about by 20% lower than in those with a thickness of 3 mm. For samples between 5 and 8 mm thick, the drop in strength is less steep. Despite the scatter of the ductility values, a dependency of ductility on the thickness is evident too.

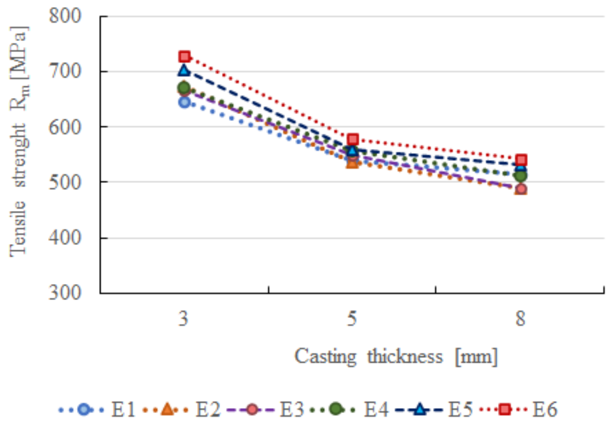

Fig. 14. Relation of the tensile strength on the casting thickness

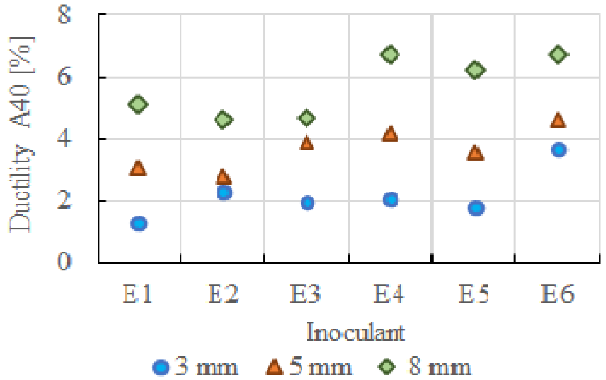

Fig. 15. Relation of the ductility on the casting thickness

3. Conclusions

The influence of the chemical composition of the inoculants of the type FeSi70 on the structure and mechanical properties of thin-walled ductile iron castings was experimentally investigated. The structure and mechanical properties were evaluated on castings of plates sized 180 by 60 mm 3, 5 and 8 mm thick, cast in a horizontal position. The In-mould method was used for the inoculation. The investigation covered 6 inoculant types which differ each other by the contents of the nucleation active elements Mg, Al, Ca, and Zr. The respective castings in the mold were placed on a common gating system with an inoculating chamber. In this way six moulds with different inoculants were cast by each test melt. The chemical composition of the melts presented was overeutectic with CE values of 4.58 resp. 4.71, the Mg_{rest} magnesium content of 0.035%. The aim of the tests wasn´t to follow the influence of chemical composition of melts but to compare inoculation effect of different inoculants.

The graphite structure and the basic metal structure were evaluated using optical and image analyses. The test HBW 5/750 was used to test the hardness of the castings. The tensile strength and the ductility were used to test mechanical properties on samples of melt E.

It was found that the graphite size and graphite dispersity were considerably dependent on the cooling rate by solidification, in test represented by the casting wall thickness. The influence of the inoculant type on graphite morphology for castings of identical thicknesses is less significant.

Dependence similar to those for hardness were also found for tensile strength where a significant drop was detected with increasing casting wall thickness between 3 and 5 mm. Here, too, an less insignificant influence was marked of the inoculants type. With the growing thickness of castings, the ductility increases, while the influence of the inoculants type on the ductility is less significant.

It was confirmed that, at a casting temperature of above 1400 ^{o}C, no casting misruns, carbides ore chill were detected.

In all castings, shrinkage areas occur along their longitudinal axis. Their occurrence and scope were confirmed by X-ray tests. The shrinkage cavities are bounded by dendrites of the primary phase. It is evident that, not even in a significantly overeutectic cast iron, cast into rigid mould, the graphitic expansion is not sufficient to compensate for the volume contraction of the metal during solidification. Due to the hight extensity of the planar dimension of the castings related to the wall thickness, the volume deficit in castings cast in the horizontal position cannot be compensated for by ingate or risers. In thin-walled ductile iron castings the required distribution of the metal temperature field has to be achieved by changing the position of casting in the mould or of the appropriate filling method which ensure directional solidification.

Acknowledgement

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