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Validation Tests of Prediction Modules of Shrinkage Defects in Cast Iron Sample

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Abstract

The paper presents the results of experimental-simulation tests of expansion-shrinkage phenomena occurring in cast iron castings. The tests were based on the standard test for inspecting the tendency of steel-carbon alloys to create compacted discontinuities of the pipe shrinkage type. The cast alloy was a high-silicone ductile iron of GJS - 600 - 10 grade. The validation regarding correctness of prognoses of the shrinkage defects was applied mostly to the simulation code (system) NovaFlow & Solid CV (NFS CV). The obtained results were referred to the results obtained using the Procast system (macro- and micromodel). The analysis of sensitivity of the modules responsible for predicting the shrinkage discontinuities on selected pre-processing parameters was performed, focusing mostly on critical fractions concerning the feeding flows (mass and capillary) and variation of initial temperature of the alloy in the mould and heat transfer coefficient (HTC) on the casting - chill interface.

Keywords: Castings defects, Shrinkage, Porosity, Ductile cast iron, Validation

1. Introduction

One of the most important criteria of quality of castings, related to period of crystallization and solidification, is definition of an acceptable level of shrinkage defects, in specific regions of a casting, which is related to location of these defects and effectiveness of riser operation. Intensity and volume distribution of these discontinuities of shrinkage origin results of balancing between demand for the liquid metal in the solidifying zones ($T_{liq} - T_{sol}$) and behavior of feeding paths between feeding-capable zones and zones presenting shrinkage demand. Assumption of critical thresholds of the feeding flows (so-called critical fractions of liquid or solid phase) is dependent on type of algorithm applied in a specific computing code (including simplifications applied in model). It is very important to experimentally validate these fractions, with quantitative reference to porosity in a actual casting. Presence of porosity

(discontinuity) in cast products is an unavoidable phenomenon, as most phases which are formed in castings decrease their volume while transiting into solid state (an exception for that is graphite phase in cast iron, what additionally complicates the feeding-shrinking processes). Generally, porosities in castings may be of shrinkage and gas origin [1]. The paper is focused on the first type, formed during change of the state of matter from liquid to solid and induced by alloy density variation [3].

In modeling of the casting processes, shrinkage phenomena and counteraction against their results are the most significant aspects for the foundry engineer. Flows between appropriate zones [2] are related to the superheating and solidification shrinkage and range of the feeding flows from the risers to the casting hot spots [4,5], with consideration of, among other things, influence of chills on directionality of solidification, dimensions and configuration of the casting walls [1]. The higher complexity of a casting shape, the more difficult it becomes to intuitively

predict the phenomena – that is when aid provided by the simulation systems becomes very useful.

The basic expectation formulated towards the casting processes simulation systems (initial version of a process is a starting point for optimization activities, by way of computer virtualization) is inspecting correctness of the initial concept about the mentioned defects of shrinkage origin. Prognosis of these defects and comparing them to an acceptability criterion formulated in receiving conditions by a client can decide about permitting production of a casting per the initial process, but usually optimization is required. That is why foundries invest in purchase and development of applications of the simulation systems.

The defects of shrinkage origin are mostly beyond repair or require expensive welding procedures (if a receiver will allow such repairs). That is why it is important to make virtual prognoses regarding the mould cavity filling stage (in range of influence of the initial temperature field on the 3D map).

Each specific grade of cast iron contains, in its database, a curve of density variability with temperature, which allows concluding about potential cumulative demand of an alloy for neutralization of shrinkage discontinuities.

Intensity of shrinkage phenomena is a result of a course of a total variability of densities of crystallizing phases with the temperature - $\rho=f(T)$. On the other hand, dynamics of generation of the solid phase (particular phases) and conditions of flow (above mentioned critical fractions, shortly named as mass and capillary [1,4]), as well as influence of gravity will also decide about location, local intensity and total volume of shrinkage discontinuities.

In the paper, based on experimental-simulation tests, selecting a simple-shaped, compacted casting of the shrinkage test (so-called Czikel test) was applied. An analysis of sensitivity of modules responsible for prognoses of shrinkage-based discontinuities on selected pre-processing parameters, including mostly values of arbitrarily (by process engineer decision) controlling the feeding flows inside a casting, is presented. The NovaFlow & Solid simulation code was subjected to these tests, with preliminary reference to the Procast code.

2. State of art

The direct effect of shrinkage phenomena occurring during the solidification is forming of discontinuities (in case of compact voids of high concentration known as the shrinkage cavities [7,8]). Such voids are, by principle, allowed to arise in risers or possibly in hot spots, when a casting process concept is incorrectly developed. The shrinkage cavity is a void inside volume of a casting, usually of shape close to conical. The shrinkage cavity is formed because of alloy contraction during cooling in a liquid state and during solidification, when a liquid (sometimes solid-liquid) phase is not allowed to flow from a riser to replenish this decrement of volume. In the most frequent case, the directional solidification condition (from the heating node the most distant from the riser to the location directly below the riser) is not fulfilled, so the so-called path feeding is not patent.

Therefore, the shrinkage discontinuities arise during casting solidification, when total volume metal shrinkage in a casting is higher than the reserves in a riser and/or if the path feeding is closed too early [7÷9].

The size and distribution of discontinuities of shrinkage origin depend on factors such as: alloy chemical composition, elements of mould processing and parameters of its pouring.

Reproduce of above described mechanisms by modules in the simulation systems is diversified and results from approach and simplifications applied by their creators. These simplifications, as well as database parameters, co-decide about effectiveness of prognoses of shrinkage discontinuities. An initial parameter, which is decisive in terms of an alloy's demand for feeding is a curve of variability of density of this alloy in function of temperature. In the earlier work, influence of this parameter was tested [2].

In a database required for computing, in the NFS CV system [10,11], the following parameters controlling forming of shrinkage discontinuities are defined: mass critical fraction of a liquid phase (designated as CLF up) and capillary critical fraction of a liquid phase (designated as CLF down). The first one indicates boundary conditions of the mass feeding flow, while the second one indicates these conditions for the capillary flow (between a framing formed by the already solidified phase).

In the Procast system [12], parameters necessary to define are (different to the NFS CV, the fractions describe the solid phase): critical fraction of shrinkage cavity forming (designated as PIPEFS), critical fraction of macroporosity (designated as MACROFS) and critical length of feeding path (designated as FEEDLEN).

In case of cooling of a zone in a casting, with increase of density while temperature drops, a phenomenon of shrinkage occurs in every element of a discrete division (FDM, FEM). In each time step, a shrinkage occurs in each element for which the solid phase fraction is lower than MACROFS and at a distance additionally considering the FEEDLEN, from an iso-surface representing the MACROFS condition. The shrinkage discontinuities in the model approach arise according the following scheme, described, among others, in [12]:

- in case when in the highest located element (cell) of a discrete division of a casting, characterized by a solid phase fraction lower than the PIPEFS assumed for calculations, a reduction of liquid/solid-liquid mass occurs, with visible lowering of its surface by values representing shrinkage demand of elements; result of this balancing comes from the gravity field,
- in the same case, but with the solid phase portion higher than the critical one (PIPEFS), partial “emptying” of a given element occurs, which translates into occurrence of shrinkage macroporosities; obviously, the elements will not be visible in the shrinkage discontinuity map as hollow volumes.

To sum up, if no element on the upper surface of a casting/riser has the solid phase fraction lower than PIPEFS, no defect of concavity of this surface (open pipe shrinkage) will occur, but only macroporosity defects will be present, possible to be modified by capillary flow, if the solid phase fraction is lower than MACROFS. Continuing, per this scheme, microporosity not liable to replenishing by feeding can form only in a zone of a casting, where the solid phase fraction is between MACROFS and $FS = 1$ [12].

To determine tendency of an alloy to form defects of shrinkage origin in a casting, a method described in the Polish Branch Standard BN-80/4051-11 was used – Figure 1 [6].

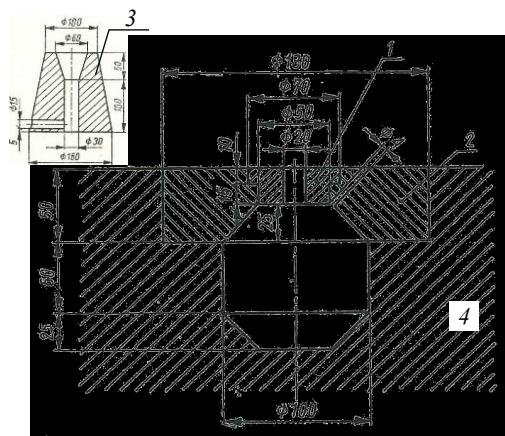


Fig. 1. Scheme of the mould, according to the standard [6].

1 - sand core, 2 – steel chill, 3 – core with gating system, 4 - actual mould

Tendency of a cast iron to form shrinkage cavities in castings can be also determined using processing tests of different shapes. Their common feature is presence of one or several heat nodes in a casting. Simultaneously, a condition of appropriately rapid filling of a mould cavity should be fulfilled, to prevent start of crystallization before the mould is filled and enabling compensation of shrinkage of the solidifying alloy this way. It is important to precisely determine pouring temperature per an assumed methodology. Application of a massive chill with heat insulation of a central hole (Figure 1) usually favors shaping of a solidification front in an upper part of a casting in a way allowing to form a compacted shrinkage cavity connected to the ambient (lack of sub-atmospheric pressure) [8,9].

3. Methodology and experimental tests

In the tests, a shrinkage test, modified in comparison to the standardized test, was used (Figure 2a). This test, according to the standard, is recommended for cast steel. This original concept, proposed one time by J. Czikel allows its usage also for different alloys, including cast iron [9]. This paper presents its application for high-silicon cast iron, with modified gating system and dimensions of upper part of flow-off core.

The mould of vertical parting plane was made, using two cores out of moulding sand based on quartz sand matrix, bound by 3% silicate resin, hardened using carbon dioxide. The core box used for manufacturing the cores is presented in Figure 2b. The assembly of complete mould was done per the scheme shown in Figure 2a.

The methodology described in the standard also comprises course of cleaning and casting finishing operations. Then, per the standard, the hole of the shrinkage cavity must be sealed and a specimen must be weighed in air and in water, using analytical scales of accuracy of at least $\pm 0,1g$.

Density of a specimen was determined using the following formula (1):

$$\rho = \frac{m_{air}}{m_{air} - m_{H_2O}} \cdot \rho_{H_2O} \quad (1)$$

where:

m_{air} – mass of specimen weighed in air, g

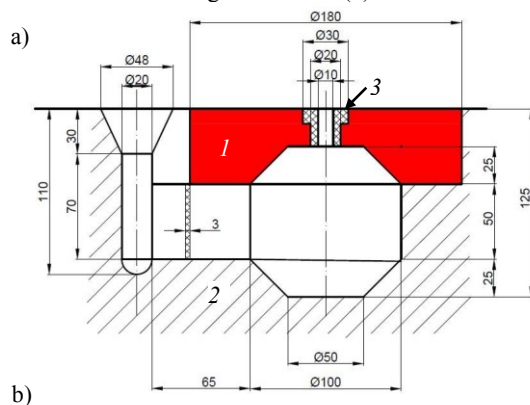
m_{H_2O} – mass of specimen weighed in water, g

ρ_{H_2O} – water density, g/cm^3 .

Sum of discontinuities (focused and possibly scattered) is determined using the following formula (2):

$$Shr = \frac{\rho_{compact} - \rho}{\rho_{compact}} \cdot 100\% \quad (2)$$

Shr – percentage discontinuity related to volume of the whole specimen (equal to volume shrinkage of the studied cast iron in defined conditions); $\rho_{compact}$ – density of an alloy, by assumption – alloy of perfect compactness, in described tests this value was approximated based on routine density study [13] of a specimen cut out of a chill interaction zone, g/cm^3 , ρ – density of a specimen determined using the formula (1).



b)

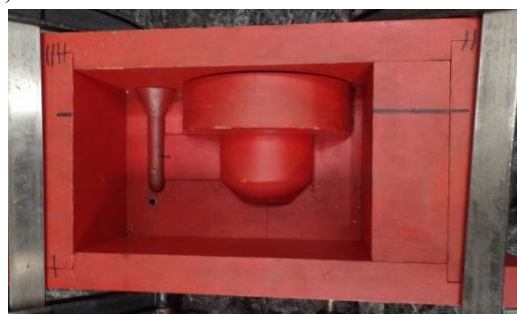


Fig. 2. Scheme of modified mould and tooling used for experimental tests: a) mould: 1 – steel chill, 2 – sand mould, 3 - sand core, b) universal core box

Figure 3 presents examples of cross-sections of castings made from two cast irons: grey GJL-300 (for comparison) and ductile GJS 400-15. Additionally, for the ductile cast iron sample, a cooling curve is presented (Figure 3c); a thermoelement was placed in a point marked in Figure 3b.

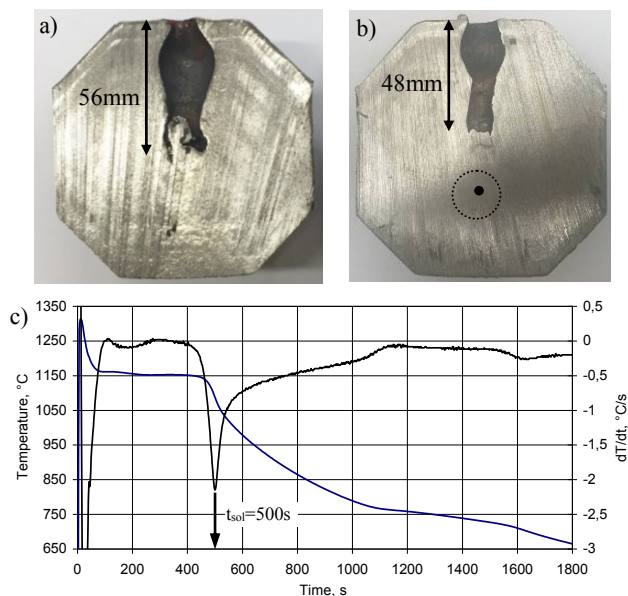


Fig. 3. The cross-section of chosen shrinkage test cast iron samples: a) grey cast iron GJL-300 [14], b) ductile cast iron GJS-400-15, c) cooling curve for ductile iron GJS-400-15 sample (pouring temperature about 1402°C; measured in point assigned by black point- in Figure 3b)

In parallel, to determine volume of the compacted shrinkage cavity, a certain method was applied (further known as SMB - *Shrinkage Method Bis*). The results are presented in Table 2.

The carried out experimental tests allowed to obtain a comparative material about validation tests of the simulation codes NovaFlow & Solid and Procast.

The size and distribution of shrinkage discontinuities were taken into account.

High-silicon cast iron of average chemical composition, presented in Table 1, was used to perform the castings.

In scope of the validation actions, so-called energetic validation was performed in the first place, consisting in identified solidification time of a shrinkage test (Figure 3c) and its comparison with solidification times obtained in consecutive simulation tests. For that purpose, successive elements of a database were selected – thermophysical material parameters (Figure 5) and, preliminarily, a heat transfer coefficient (HTC) on the casting-chill interface, at a level of 400 W/m²K [15] was considered.

Thermophysical parameters were assumed on the basis of chemical composition of the cast iron (see Table 1, sim), introduced into the NFS CV database for the ductile cast iron (EN-GJS-600 – Figure 5a, as well as values of latent crystallization heats: $Q_{cr}=160$ J/kg, $Q_{eut}=251,8$ kJ/kg and modified density curve, considering an effect of eutectic graphite expansion; this effect was arbitrarily decreased to value of -0,6%). Averaged chemical composition was introduced, as shown in Table 1 (it must be emphasized, that suitable standard EN PN 1563:2012 defines only approximate maximal concentrations of only three elements: Si – 4,3%, Mn – 0,5% and P – 0,05%).

Table 1.

Chemical composition of GJS-600-10 cast iron (aver-average, sim-used to define chosen simulation parameters)

No	C	Si	Mn	P	S	Cu	Cr	Mg	Al
AVER	2,9- 3,1	3,9- 4,2	0,3- 0,4	0,02- 0,03	0,01- 0,02	0,2- 0,4	0,05	0,04- 0,05	< 0,05
SIM.	2,98	4,13	0,32	0,025	0,01	0,24	0,03	0,048	0,02
EN PN 1563:2012	-	4,3	0,5	0,05	-	-	-	-	-

For calculations using the Procast code, classical cast iron GJS-600 was selected out of the database and computing was done using micromodel for the introduced chemical composition (see Table 1, sim), Fig. 5b).

The edge length of a homogeneous FDM (Finite Difference Method) mesh in the NFS CV code was assumed as 1,5 mm (Fig. 4c), while in the Procast code a FEM (Finite Element Method) mesh was formed by tetrahedrons of edge length equal to 2 mm (Fig. 4c).

Thermophysical parameters of a mould and a chill were assumed both the same in the NFS CV and in the Procast code (Carbon steel – Figure 5c). Properties of the mould sand were preliminarily assumed from the database developed in earlier tests [2,13]: thermal conductivity = 0,7 W/mK, specific heat = 1000 J/kgK, density = 1500 kg/m³).

Real solidification time about 500 seconds was achieved in a satisfying way for both codes (underestimation error was about 5%).

On the basis of the initial temperature map of casting obtained for these thermophysical parameters (after filling the mould cavity) it was estimated that its average value is 1360°C (± 10°C) and is lower than temperature of a cast iron stream poured into mould by approx. 40°C.

Comparing the results of energetic validation and results of shrinkage test (for identical set of pre-processing parameters) was made in the following conditions:

- considering variability of temperature field resulting from the simulation of the mould cavity pouring,
 - with assumption of a constant average temperature of liquid cast iron in the whole volume of the mould cavity - 1360°C
- the satisfying approximation was obtained for both results, which was a starting point for a decision, to base upon a case of the constant-value initial metal temperature in mould cavity in the sensitivity testing procedure.

Then, sensitivity tests were conducted for both above mentioned simulation codes, considering only distribution and portion of volume of shrinkage discontinuities. The following parameter values out of the database were subjected to testing:

- initial alloy temperature in the mould cavity, in the range from 1290°C to 1400°C (that is, +40°C and -70°C in relation to the temperature from the energetic validation)
- HTC on the casting-chill interface in the range from 300 to 2000 W/m²k (that is, +1600 and -100 in relation to value from the energetic validation); as a comment to this assumption, a fact must be mentioned that appearing of a shrinkage gap between conical upper surface of a casting and a steel chill happens in a yet unrecognized way (the authors anticipate experimental exploration of this phenomenon in a successive stage of tests).

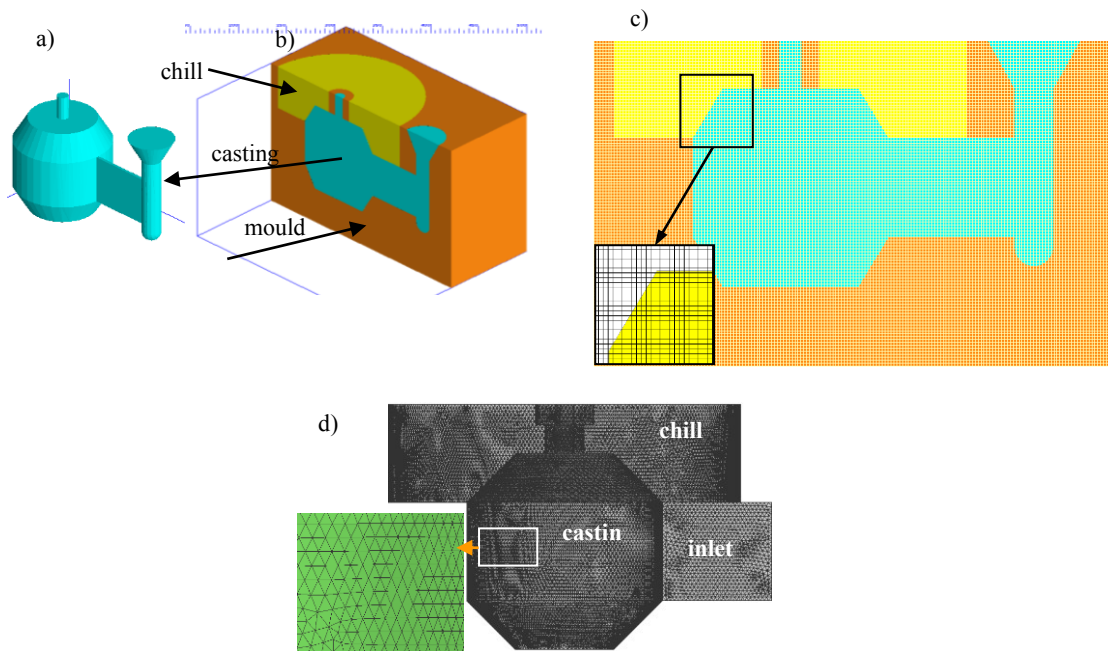


Fig. 4. Shrinkage test CAD geometry in the NFS CV system: a) 3D view, b) section through the casting-mould system, c) FDM mesh (“cube” edge size 1,5 mm), d) FEM mesh (tetrahedral mesh of edge length 2 mm)

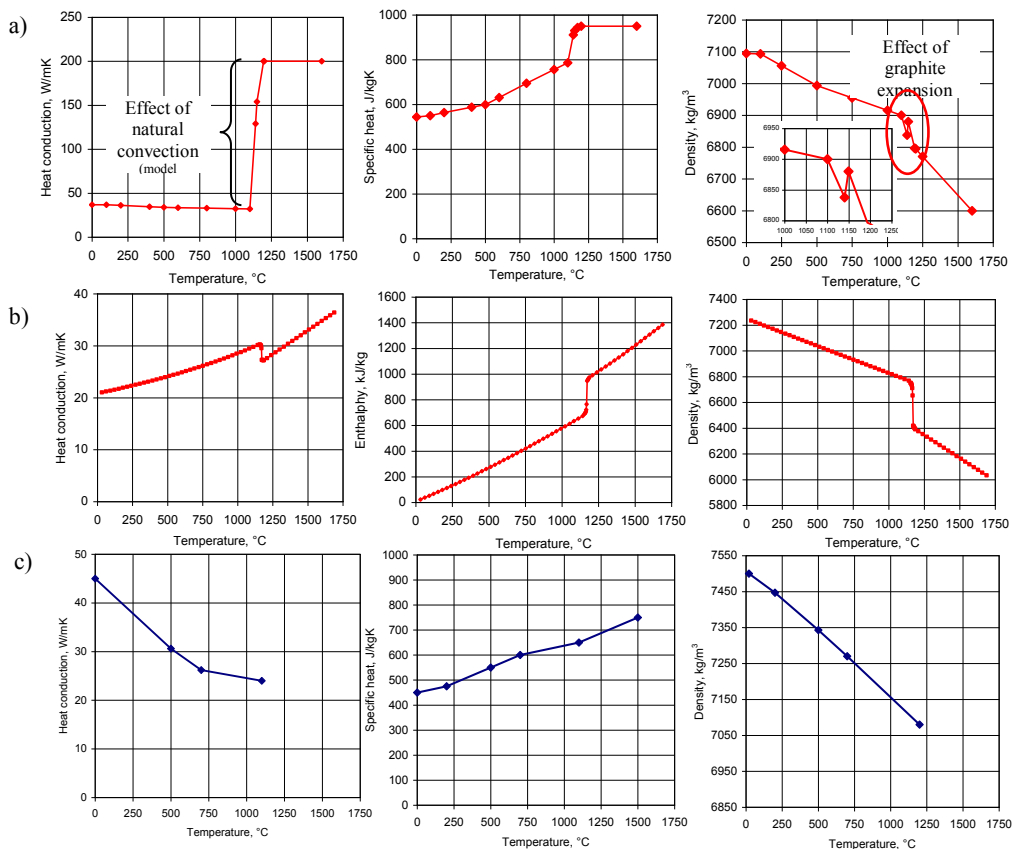


Fig. 5. Materials database applied to simulation: a) alloy parameters in NFS CV data base $T_{liq}=1193^{\circ}\text{C}$, $T_{eut}=1145-1100^{\circ}\text{C}$, $T_{sol}(\text{kinetic})=1092^{\circ}\text{C}$, b) alloy parameters in Procast data base, $T_{liq}=1187^{\circ}\text{C}$, $T_{eut}=1172-1160^{\circ}\text{C}$, $T_{sol}=1152^{\circ}\text{C}$, c) steel chill used for both codes

- critical fractions of a liquid phase (NFS CV code), that is CLF (up – mass feeding between 0,1 and 0,95% and down – capillary feeding between 0,1 and 0,95%) and of a solid phase portion (Procast code), that is PIPEFS and MACROFS in the same range (between 0,1 and 0,95%); such an assumption must be connected with morphology of solidification front and, especially in area of lower values of critical fraction of liquid phase, it indicates hypothetical permission of feeding flows (mass and capillary, respectively) of the solid-liquid phase, of relatively low values.

The CAD geometries of the mould (with chill) – shrinkage test castings layout was prepared using the Siemens NX software (Figure 4a and b).

Diagrams presented in Figure 5 are fundamental elements of the database. Despite similar chemical composition, differences between some thermophysical parameters of a cast iron are a result of empirical formulas used independently in the both codes and of simplifications of models applied in the computing algorithms. Interchangeability of the databases may comprise only selected parameters and must be preceded with an analysis. It concerns especially variability of the density curve with the temperature. In comparison with an experimentally determined value of the volume feeding shrinkage (see Table 2):

- for the NFS CV – value of total shrinkage solidification between the liquid and the solid state is 1,5% (where the graphite expansion effect is approx. -0,6%), so it is higher by approx. 50% in comparison with the measured values (see Table 2),
- for the Procast – solidification shrinkage (from the empirical formula assigned to this code) is as much as 5%. On this stage of research, it was decided not to interfere in values and course of density variability with temperature.

4. Analysis of results of experimental-simulation tests with elements of validation of simulation codes

The results of the experimental tests, shown in Figure 6, present vertical cross-sections of selected test castings, made as perpendicular to the knife gating system. Under the photographs, volumes of shrinkage cavities are presented, determined using the SMB method, juxtaposed in Table 2 with results of the shrinkage coefficient Shr (this procedure is described in chapter 3). Results of porosity and density portions of a casting are repeatable with assumption of relatively low differences in the chemical composition. However, shape of discontinuities is variable. That is why in the validation tests, averaged (simplified) shape of a defect must be assumed, with emphasis put on its location and size (volume).

The Scenario of tests of codes sensitivity assumed, that thermophysical parameters of cast iron and mould fulfilling the energetic validation criterion (for NFS CV), including T_{init} and HTC, will be a reference point for the further analyses. Stages of these tests consisted in testing for location and volume of discontinuities of shrinkage origin, in the following order:

- influence of combination of CLF up and down fractions,
- influence of homogenous temperature T_{init} ,
- influence of HTC.

It was assumed that thermophysical parameters fulfilling the energetic conformity with the simulation results (criterion of solidification time in a selected point of a casting) will be valid equally in all the experiments. The tests of influence of the CLFu and CLFd critical fractions are presented below. The analysis was started from the case presented in Figure 7.

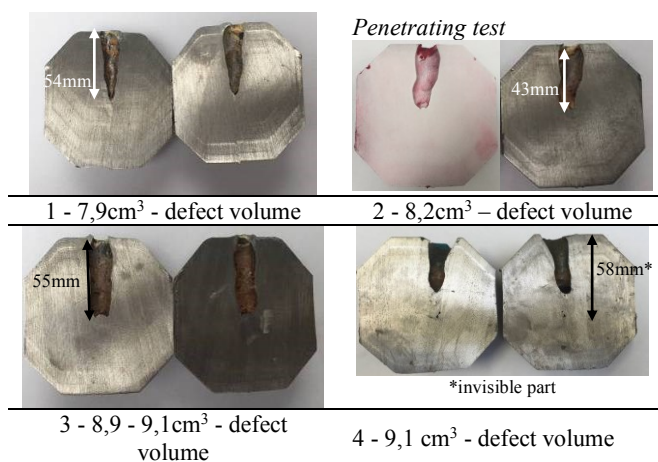


Fig. 6. Selected sections of castings made from ductile cast iron GJS-600-10 with presentation of volume of shrinkage cavities (compare with results in Table 2). For a selected, representative case, penetrating tests (PT) are presented, they did not reveal presence of dispersed porosity below clearly visible pipe shrinkage

Table 2.
Results of experimental tests (examples)

No	Casting weight in air [g]	Casting weight in water [g]	Density considering defects [g/cm^3] (Eq.1)	Shrinkage [%] (Eq.2)	Experim. SMB Porosity volume [cm^3] / [%]	Defect Range (a+b) [mm]
1	4507,5	3866,3	6,98	0,92	7,9/1,13%	54
2	4406,1	3781,1	6,98	0,92	8,2/1,17%	43
3	4510,6	3870,0	6,98	0,92	8,9/1,27%	55
4	4390,5	3760,9	6,97	1,06	9,1/1,3%	58

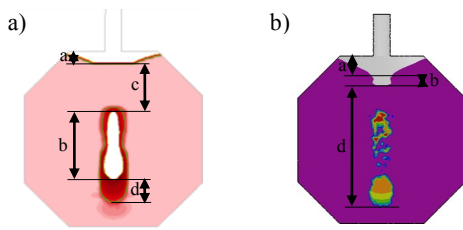


Fig. 7. Example of designation, a) shrinkage prognosis for critical fractions proposed for all grades of ductile cast iron by NFS CV 6: CLFu = 0,7 and CLFd = 0,3. Solidification time (compare Fig. 3) 450s, high pipe shrinkage a = 6,5 mm, axial down pipe shrinkage b = 38,5 mm, bridge a/b c = 28 mm, shrinkage porosity zone d=13mm., %volume porosity Shrinkage=2,55%; b) segments fitted adequately to result of Procast prognosis for PIPEFS=0,3 MACROFS=0,7: a=13,5mm, b=4mm, c=0, d=74mm

As results from the Figure 7, a compacted discontinuity (pipe shrinkage = 1,0, white-marked field) occurs in two clearly separated areas, through the so-called a/b bridge. It is incompatible with experimental results (Figure 6).

Figure 8 presents dynamics of volume increase of sum of all shrinkage discontinuities (a+b+d) (as a percentage of the whole casting volume). The final value represents the density curve in Figure 5a.

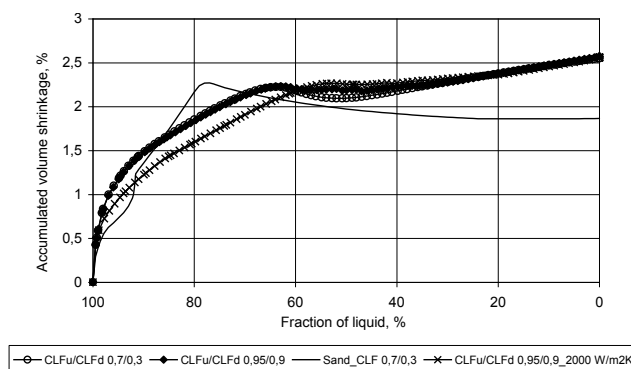


Fig. 8. Diagrams of total increase of shrinkage discontinuities volume in function of decrement of liquid phase in the whole casting (simulation result from the NFS CV for the 0,7/0,3 and 0,95/0,9 cases). Visible graphite expansion effect, per the density curve in Fig. 5

Comparatively it was shown the graph for the mould completely made of sand i.e. without chill (decreasing the total shrinkage to about 1,9% due to lower kinetic temperatures T_{sol} calculated from the chemical composition by hidden algorithm NFS CV - for which FL = 0)

To evaluate influence of the CLFu/CLFd ratio, series of simulations were made, paying attention to location of particular discontinuities. The results are presented in Fig. 9. As results, for the CLFu = 0,7, no fraction combination led to joining of shrinkage a and b (c value

above 0). Other combinations were also studied, where CLFu was equal to +0,2 and -0,2. Only for the greater value CLFu = 0,9, the high pipe shrinkage (under the chill) and the axial down pipe shrinkage (meaning no a/b bridge presence – c=0) were obtained.

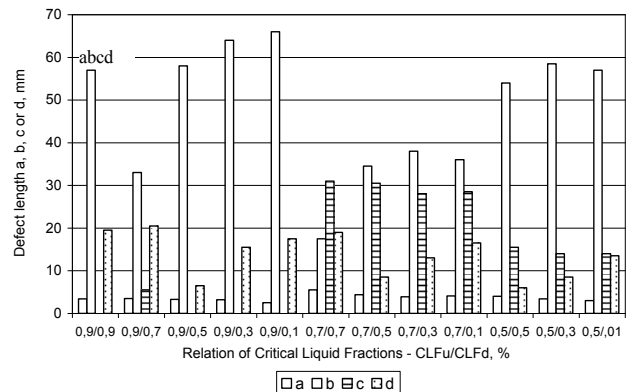


Fig. 9. Juxtaposition of NFS CV simulation parameters of shrinkage discontinuity location for the selected CLFu/CLFd combinations

For the CLFu/CFLd = 0,9/0,9 fraction ratio combination, an already satisfying approximation of defect length: a+b parameters to experimental results was obtained. It means that for the studied ductile iron, possibilities of the mass and capillary feeding needed to be stopped relatively quickly, on the level of 10% of the solid phase. Further, detailed tests led to indication of the CLFu/CFLd ratio best fitted to the experiment, equal to 0,95/0,90. For this case, tests of the NFS CV code were made, regarding interaction of the initial cast iron temperature and HTC of the casting-chill on prognoses of geometry of location and shape of the compacted shrinkage discontinuity.

In Figure 10, by pattern of a concept from Figure 9, results of these additional tests are presented, considering influence of higher and lower initial temperature of the cast iron after filling the mould and influence of the variable HTC between chill and cast iron. The obtained results confirm intuitive predictions of directions of influence of selected variable parameters for the CFLu/CFLd=0,7/0,3 case.

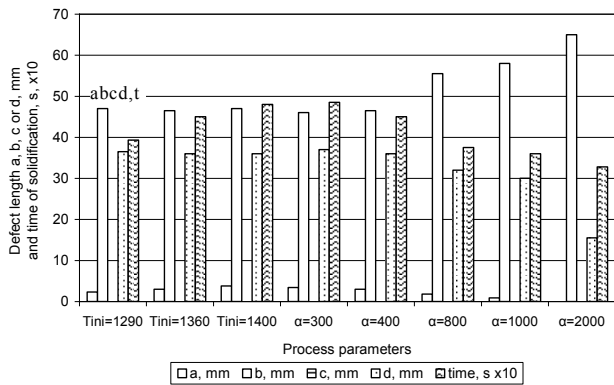


Fig. 10. Results of additional series of simulation tests (NFS CV) for CLFu/CLFd = 0,7/0,3, considering influence of the initial temperature and the HTC (for all cases c = 0)

The best conformity (energetic validation) was achieved for the initial temperature of 1360°C and HTC = 400 W/m²K. If the energetic validation was omitted (not placing a thermocouple during the experiment) and the validation was based only on the basis of the compacted pipe shrinkage, value of the HTC (representing a level of interaction between chill and casting) best approximating location and size of the focused pipe shrinkage would be approx. 1000 W/m²K. Solidification time obtained from the calculations would be then reduced to approx. 360 s, so the energetic validation would not be achieved.

Simultaneous energetic validation with consideration of HTC will be a subject of further tests. The above-mentioned results allow concluding, that total capping of the upper real surface of a shrinkage specimen means that during the first period of solidification, value of the HTC can achieve or even exceed 2000 W/m²K. Then, this value will significantly decrease because of a forming shrinkage gap and gravity direction. The condition of energetic validation may be then fulfilled.

It needs to be added, that in neither case of calculations performed using the NFS CV, even for the case best fitting the energetic validation criterion and location of the pipe shrinkage, value of the d parameter is approx. 45 mm.

Two cases from the above were selected to compare pipe shrinkage prognoses with results from the Procast code.

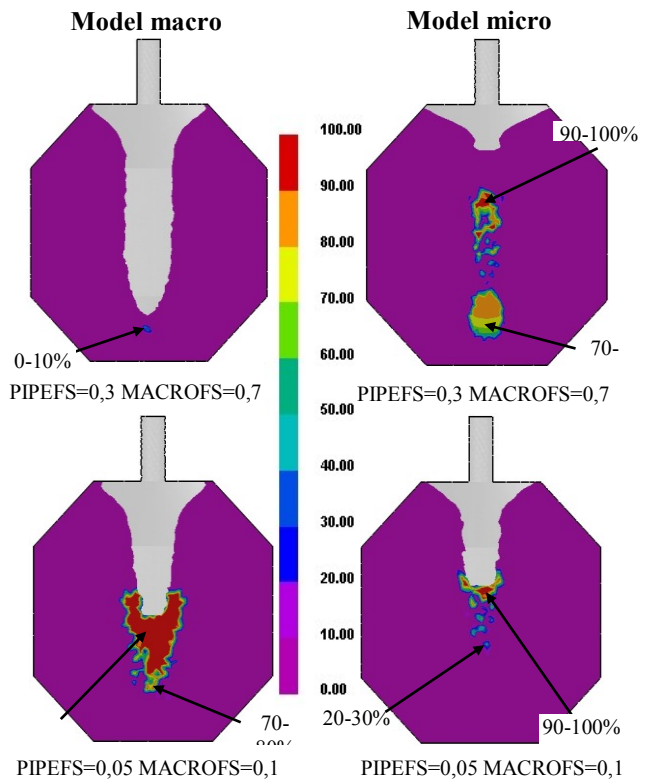


Fig. 11. Prognosis of shrinkage origin defects obtained using the Procast system for two combinations of critical fractions, that is PIPEFS = 0,3 MACROFS = 0,7 and PIPEFS = 0,05 MACROFS=0,1 (for two macro and micro models) Location of pipe shrinkage (a+b) and macro-shrinkage (d) results out of a juxtaposition presented in Fig. 12.

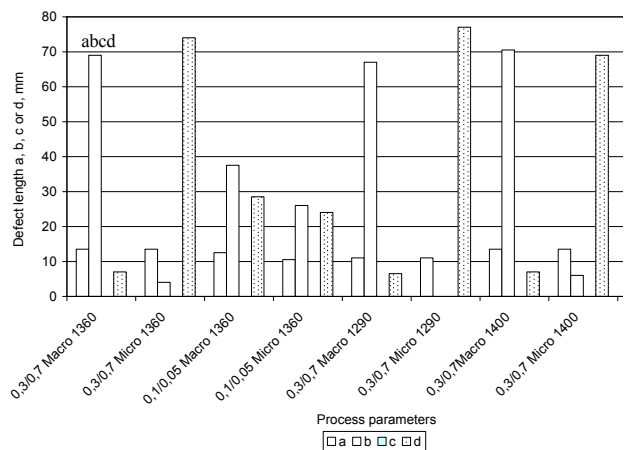


Fig. 12. Results of additional series of simulation tests (Procast) for PIPEFS/MACROFS = 0,3/0,7 and 0,05/0,1, with consideration of influence of initial temperature (for all cases, c=0). Calculations performed for HTC = 400 W/m²K

Evaluating the Procast modules for shrinkage discontinuities prognosis and comparing them with the NFS CV modules, it can

be stated that boundary values of critical fractions of the liquid and the solid phase ($CLF_u = 0,7$ is equal to $PIPEFS = 0,3$ and $CLF_d = 0,3$ is also equal to $MACROFS = 0,7$) suggested by both systems do not lead to obtaining results representing conditions of the experiment. Values of the critical fractions, which were close to results of casting experiments in the most satisfying way (for NFS CV: 0,95/0,9, for Procast: 0,05/0,1) indicate, that algorithms balancing the feeding flows compared with the local shrinkage demands are constructed in a similar way.

Similarly, as in the case of the NFS CV tests, influence of the initial temperature is visible and logical.

Both codes indicated on the presence of shrinkage porosity below the compacted defects of pipe shrinkage type. These defects were not detected in the real castings of the shrinkage test. It can be dependent not only on tested critical fractions, but also, for example, on assumed variability of the density-temperature curve $\rho=f(T)$. This variability $\rho=f(T)$, influencing dynamics of the shrinkage-expansion phenomena in cast iron, is dependent also on the local rate of heat extraction out of a casting. Micro and macro modules of the Procast code give significantly different results in terms of location of discontinuity defects (Fig. 12).

5. Summary

Based on the conducted tests, the following conclusions can be drawn:

- shrinkage test is a relatively simple experiment, allowing for determination of cast iron tendency to create discontinuities of shrinkage origin, which may be also used for validation of a module responsible for prognoses of shrinkage defects,
- validation should comprise identification of parameters in a material database used by a given module, especially including critical fractions of mass and capillary feeding, but also, earlier, the rest of thermophysical parameters influencing dynamics of solidification and heat transfer processes in the casting-mould system,
- among these thermophysical parameters, the most important one (especially for cast irons) is variability of alloy density with temperature $\rho=f(T)$, because of a compensating interaction on shrinkage of the graphite matrix expansion,
- although tests of both simulation codes brought similar results for the selected parameters, no full conformity was achieved, it requires further validation tests matching the experiment results,
- feeding-shrinking mechanisms tested using identical thermophysical parameters of the casting-mould system for micro and macro models (Procast) shown significant differences in prognoses of shrinkage discontinuities; the micro model, based on a different latent heat emission algorithm than in the macro model (close to that used in the NFS CV) decides about different course of virtual crystallization.

To sum up, each foundry simulation system requires validation tests based on properly planned and realized experiments of making the test castings, ideally of relatively simple shapes. Besides the energetic validation (with instrumentation of the casting-mould system), it is very important to consecutively use destructive and/or non-destructive testing of

shrinkage discontinuities in the castings. This procedure, rules of which are described in this paper, should allow obtaining more complete and reliable parameters of pre-processing. Validation realized using actual castings, especially those of complex shapes and only on the basis of the visual testing (VT) and non-destructive testing (RT, UT) of castings may be burdened with an error of unknown tolerance margin. *Par default*, recommended values of critical fractions of feeding in the simulation systems used by many foundries did not give expected values of discontinuity prognoses. It confirms necessity of analysis of phenomena occurring in each specific case of the casting-mould system, with an attempt of generalizing on similar material-technological solutions.

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