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ARCHIVES
of
FOUNDRY ENGINEERING

DOI: 10.1515/afe-2017-0115

Published quarterly as the organ of the Foundry Commission of the Polish Academy of Sciences

DE GRUYTER OPEN

ISSN (2299-2944)
Volume 17
Issue 3/2017

196 – 204

Discussion on Usability of the Niyama Criterion for Porosity Predicting in Cast Iron Castings

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Received 17.04.2017; accepted in revised form 28.07.2017

Abstract

The paper refers to previous publications of the author, focused on criteria of casting feeding, including the thermal criterion proposed by Niyama. On the basis of this criterion, present in the post-processing of practically all the simulation codes, danger of casting compactness (in the sense of soundness) in form of a microporosity, caused by the shrinkage phenomena, is predicted. The vast majority of publications in this field concerns shrinkage and feeding phenomena in the cast steel castings – these are the alloys, in which parallel expansion phenomenon does not occur as in the cast irons (graphite crystallization). The paper, basing on the simulation-experimental studies, presents problems of usability of a classic, definition-based approach to the Niyama criterion for the cast iron castings, especially of greater massiveness, for prediction of presence of zones of dispersed porosity, with relation to predictions of the shrinkage type defects. The graphite expansion and its influence on shrinkage compensation during solidification of eutectic is also discussed.

Keywords: Cast iron castings, Graphite expansion phenomenon, Simulation codes, Niyama criterion, Experimental validation

1. Introduction

Using simulation codes (systems) in the worldwide foundry has been a standard for at least a dozen years. They are used by specialists – process engineers – to optimize projects of concepts realized practically for all the cases of the foundry technology and for castings out of all the technical alloys. An advancement, that is ongoing in area of these tools, aiding work of a process engineer, is continuous. Creators of the codes, who specialize in supplying subsequent upgrades, offer new solutions from time to time, containing improvements and additional modules. These modules are developed on the basis of studies and experiences and in the vast majority of cases, such a version of code can include gradual elimination of the selected simplifications of models, completion of the databases and the new post-processing tools, mostly criteria allowing expansion of possibility of results interpretation in the casting-mold system. These modules stay within the scope of soft-modelling, which is mostly based on an empirical approach. It is expected, that they will expand the possibility of using the codes in foundries, meaning obtaining of more and more precise prognoses of available parameters for prediction of quality of a casting.

Among the post-processing criteria, an important role is played by a criterion known as the Niyama criterion (by the first author of the paper published in Chicago in 1982 [1]). It is the most frequently cited and applied gradient criterion, /based on an interpretation of physical phenomena occurring in a final phase of an alloy solidification. In this period of the process, positive local balance of loss of volume caused by shrinkage and volume resulting out of feeding flow is of particular significance, in conditions where the flow is particularly difficult, and when it occurs in between the skeletal spaces, meaning between the solidified phases. The more unfolded is the "coast line" of partition between the solid and the liquid phase, the higher is the flow resistance. It concerns especially the space between arms of dendrites.

Degree of complexity of a local approach to balancing of shrinkage and compensative phenomena increases, when one of the crystallizing phases (graphite in a cast iron) is a source of expansion (almost 3%) and takes active part in the occurring phenomena. A problem of usability of a classic approach to the Niyama criterion in aspect of the mentioned phenomena during solidification of cast iron castings will be presented in this paper.

2. Specificity of phenomena and local balance of shrinkage-expansion occurrences

Experimental studies on phenomena accompanying crystallization of an austenitic matrix and graphite for the particular cast iron grades, supported by theoretical considerations, allowed understanding of physicochemical foundations of these phenomena. Feeding of the solidifying subeutectic cast irons, in a period preceding crystallization of an eutectic phase, is actually done in the same way as in the case of alloys, that do not create this expanding phase at all (cast steel and non-ferrous alloys). Analysis of a process of solidification of the cast irons, on a further stage, requires consideration of compensative eutectic graphite expansion and actual local flows in the balance of need for the liquid metal. In a rather qualitative approach, this was described in many papers, which the author does not intend citing, as it is a common knowledge. Some elaborations, by Karsay (Fig. 1), among others, should be considered as a classic here.

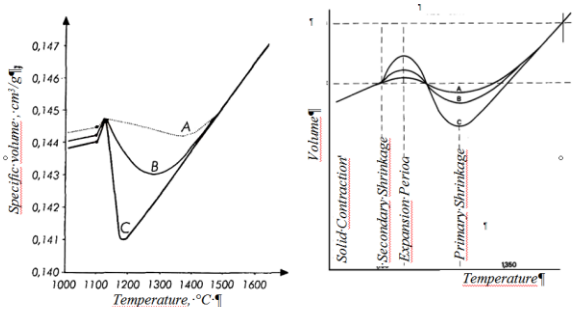

Fig. 1. Classic Karsay hypothesis regarding changes of specific volume during solidification of a chosen nodular cast iron related to variable metallurgical quality (left): A – very high, B – average, C – very low, and approximate scheme of those volume variability (right) [2]

This pictorial review allows to conclude, that shrinkage-expansion phenomena of various dynamics are possible. The increase of the specific volume of the solidified cast iron that results from the expansion of eutectic graphite can be expressed as a decrease of the specific density of this cast iron and is approximately about 185 kg/m^3 for the cast iron C and only about 25 kg/m^3 for the cast iron A.

Regarding absolute values of specific volume presented in Figure 1 – they are, at most, only approaching values available in databases of simulation codes.

Influence of metallurgical quality of a cast iron on course of its solidification is generally known from the experience of foundries. In the end, it affects percentage of defects of shrinkage origin. Quality of castings is influenced by a number of factors, starting from the metallic charge, through time and temperature conditions of melting, materials and conditions of the off-furnace treatment and conditions of introduction of a cast iron into a mold. It is often difficult to claim repeatability of the metallurgical quality, even for a specific grade of cast iron, of chemical composition compatible with a given standard. This fact translates into quantitatively non-repeatable balancing of effects of the shrinkage-expansion phenomena and uniqueness of discontinuity defects in subsequent series of castings, coming from different melts.

The stress put on these problems is a result of a fact, that cast iron castings are 75% of the worldwide foundry production.

Therefore, it is more and more common to introduce the DTA (Differential Thermal Analysis) systems [3,4] in the cast iron foundries and equipping these systems with databases created on the basis of own research, realized in a particular foundry. It allows obtaining knowledge about metallurgical quality and its stability, what is done on the basis of parameters coming from analysis of a cooling curve of a standardized cast iron sample, of volume not higher than 50cm^3. At the same time, a sample is casted for the chemical composition tests. Many cases of improvement of stability of quality of a liquid cast iron in specific foundries can be cited. To maintain effectiveness of such a system, it is required to have it constantly, professionally monitored by specialists in a foundry.

It needs to be added, that it does not mean, that conditions of obtaining this stability, as well as values of parameters obtained from a thermal analysis, will be identical in particular foundries. This problem, as it is known, requires individual approach and will not be further considered in this work.

Effects of the shrinkage-expansion phenomena, that are caused by metallurgical quality of cast iron, are overlaid with influence of mold rigidity, especially for the nodular cast irons, as well as influence of massiveness of castings, along with diversification of wall thicknesses. It creates a particularly difficult situation, when there is a need of adjusting databases applied in a simulation system (code) and it must be unquestionably stated, that simulation of solidification phenomena of cast iron castings is full of challenges. The author paid attention to this fact multiple times in his previous publications.

It is an important problem to identify one thermo-physical parameter in a database, that should be the best one to illustrate the described phenomena. It is the variability of the cast iron density, particularly in range between temperature of pouring and temperature of real solidus. In [5], results of experimental-simulation studies of the shrinkage-expansion phenomena, on the basis of a standard sample for testing inclination of ferrous alloys to create focused discontinuities of the pipe shrinkage type were presented. A sample casting was a compact one (close to a sphere), of approximate volume of 0,815 dm^3. In the summary of

[5], it was stated, that actually, among all these physicochemical parameters, variability of an alloy density in function of temperature, ρ=f(T), is the most significant (particularly for the cast irons), because of dynamic compensative interaction of shrinkage of matrix and expansion of graphite. In [5] satisfying compatibility with the experiment was not achieved yet. It requires continuous validation studies, adjusted to conditions of an experiment, including shape, configuration and size of a casting.

An important conclusion of this research was also a statement concerning the Critical Liquid Fraction. The CLF used in the NF&S system needed to be increased to a value above 90%, to obtain the best approximation of location and focusing of a shrinkage defect in the experimental casting.

Both these facts mean, that in order to effectively use certain modules (containing algorithms unknown to the user), the databases need to play a correcting role towards obtaining compatibility with an experiment. In this particular case, it regards shrinkage and feeding flow from the solid-liquid area, where fraction of the liquid phase, which is local in time and space, is higher than the CLF_{crit}.

3. State of art on feeding criteria. Special place of Niyama criterion

The question arises – to what end the post-processing of simulation code can be supplemented with additional criteria predicting zones in danger of shrinkage porosity? As it is known, a basic result of simulation computations (main processing) are temperature fields of the casting-mold system, recorded for all of its nodes, in set time steps. On this basis, time and space parameters resulting out of variability of the field are secondarily calculated and local properties of a casting are forecasted. Among other things, this pertains to arrangement and intensity of discontinuity defects. For each cell, the algorithms balance out the need for shrinkage (resulting from the ρ=f(T) function), then it is compared with capability of supplementing feed from the surrounding cells, with consideration of law of gravitation. So-called feeding paths remain not obstructed, when amount of the liquid phase is high enough to allow existence of the feeding flow (above CLF_{crit}). Breaking the feeding path is equivalent to forming of a shrinkage cavity.

The mentioned gradient feeding criteria go outside the range of predictions of shrinkage cavities, estimated as a result of the above mentioned mass balance.

As early as during the initial analysis of morphology of the solidification front, meaning volume degree of dispersion of the solid-liquid phase, influence of intensity of cooling of a casting can be observed, manifesting itself by value of temperature drop through the section of a casting wall. Reaching back to history, attempts at determination of influence of the temperature gradient on morphology and, finally, state of defects in castings, were first made in the beginning of the 50s (Pellini and Bishop [6], citation and commentary in work [7] by Wlodawer). Universalization of the gradient criterion done by Niyama and his team [1] consisted in interpretation of Darcy's law, with implementation of appropriate simplifications for the model, regular dendritic front. In [1], a relationship of pressure drop in the inter-dendritic canal is introduced, for a hypothetical point x_c positioned between branches of two dendrites ($1 < f_L > 0$,) and a basis (bottom) of the crystallization front ($f_L = 0$):

$$\Delta p = \frac{\mu \cdot \beta \cdot F_L \cdot \Delta Q_C}{(1-\beta) \cdot K} \cdot \left(\frac{G}{\sqrt{R}}\right)^{-2}$$

where: μ – absolute viscosity of an alloy, β – solidification shrinkage, f_L – liquid fraction, ΔQc – temperature drop in a capillary between x_c and a basis of dendrites, K – permeability of an area, G – temperature gradient, R – average velocity of the temperature drop (local cooling speed) [1].

Consideration of the inverse proportional relationship between Δp and square of G/√R (or, as proven in the further part – G/V, where V is a velocity of movement of the front) and arrangement of points on the diagram of G/√R = f (local solidification time) is presented in a comparative juxtaposition in Fig. 2a and 2b.

The proof of universality of the criterion was backed up by Niyama through studies of solidification of cylinders made out of various grades of cast steel, of diameters between 30 and 90 mm [1]. The G/√R expression (ratio of gradient and square root of cooling velocity of a fed element, as results out of volume discretization method), calculated in an identical volume approach of neighboring elements, for a range of cast steel castings studied by Niyama, takes a value of 0,9 – 1,5 $(K \cdot min)^{1/2}/cm$ (Niyama arbitrarily assumed G/√R = 1 as a boundary value). Higher values of G/√R were obtained for thinner castings, it may indicate dominating influence of the gradient.

Note that in newer publications there appeared a unit Ny $(K \cdot s)^{1/2}/mm)$, not corresponding to the numerical value of a classic unit from [1]. This means that the Ny limit values given by Niyama should be divided by 1,29 ($Ny_{classic\ Niyama}$.=1,29·Ny_{new}.

Hansen and Sahm [8] signalize, that the problem is far more complex and description using the G/√R expression should be treated as inaccurate. They propose an empirical criterion parameter expressed as $G^a/(\sqrt{R})^b \cdot u^c$·, in which the G/√R expression is modified, introducing additionally u – velocity of the capillary flow. The a, b and c coefficients are of empirical type and they allow adjustment of this doubly modified gradient to results of an experiment.

Using gradient-kinetic parameters of an area of the solidification front, in author's opinion means simultaneous evaluation of influence of its morphology on feeding (of course with some approximation due to the differentiation of the local solidification front morphology). By use of the G/V parameter, being a square of G/√R, a known criterion of constitutional **undercooling** is determined, used for evaluation of conditions of the front morphology, meaning a border between the liquid and the solid-liquid phase (reference to real T_L isotherm). Formally, it's related to the relationship on constitutional undercooling which occurs if:

$$\frac{G_L}{V_L} < -\frac{m_L \cdot C_0(1-k_0)}{k_0 \cdot D_L}$$

where: G_L and V_L – gradient and velocity of movement of the liquidus front T_L, respectively, m_L – slope of equilibrium liquidus line, C_0 and k_0 – average contents of an alloy admixture and coefficient of its partition, respectively, D_L – coefficient of diffusion of an admixture element in the liquid phase.

In the case of computer simulation concerning the solidification front, the G/V must be referred to the 3D discretization mesh of a casting subarea.

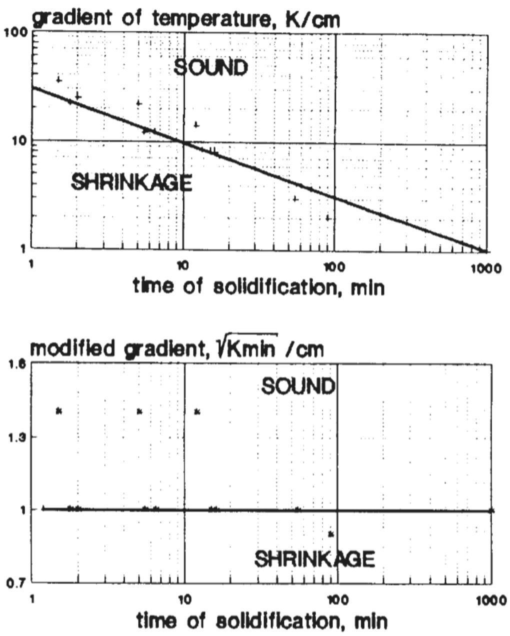

Fig. 2. Criterion of the gradient G (top) and the modified gradient G/√R (bottom), determined for the cast steel cylindrical castings, of dimensions between 30 and 90 mm, various grades of cast iron (original figure published in [1])

The modified gradient method (other name for the Niyama gradient criterion) pretends to be an universal and original criterion, according to [1]. The comparison below, with another criterion, known as the time gradient K_τ, shows if it really is.

$$K_\tau = \frac{\tau_2 - \tau_1}{\Delta l \cdot \sqrt{\tau_1}} = \frac{1}{V_{sol}} \cdot \frac{1}{\sqrt{\tau_1}} \approx \frac{G}{V_{sol}} = (\frac{G}{\sqrt{R}})^2$$

The time gradient, according to [9] is expressed by a ratio between times τ_2 and τ_1 (τ_2 and τ_1 times are solidification times of the fed and the feeding, neighboring parts/cells of a casting, respectively, while Δl is a distance between them).

After further transformations, assuming that V_{sol} is a velocity of movement of the "solidus" isotherm in one of the possible feeding directions, $1/\sqrt{\tau_1}$, according to Niyama's studies [1] can be imagined as an expression proportional to G (the temperature gradient). Further transformation is a result of a fact, that a scalar product of the vectors of gradient G and velocity of the "solidus" isotherm movement V_{sol} is a velocity of cooling of an analyzed point, representing a locally considered micro-area. Therefore, a co-relation between criterions of the time gradient and the modified gradient was obtained, as following:

$$K_\tau = const \cdot (\frac{G}{\sqrt{R}})^2$$

As can be concluded from the above juxtaposition of the selected criteria (the more detailed analysis was performed in [10]), the criterion known under name of Niyama showed up both before and after 1982, as quite coherent "thermal" approach to conditions present in a region of the solidification front. Morphology of this front decides about course of the shrinkage-feeding phenomena.

Occurrence of the graphite expansion phenomenon in the solidification front region (in the solid-liquid phase), mentioned in the chapter 2, generates a question, if criteria of gradient type can be treated as effective indicators predicting presence of the shrinkage porosities.

Problems of usability of the Niyama criterion (Ny) are still a topic of publications, indicating a method of its use, with the following Ny applications:

- for alloys other than the cast steel (Ni alloys [11], Al-Cu alloys [12,13,14]),
- for a wider group of cast steels, including the austenitic and duplex ones [11.13],
- with proof of usability for prediction of hot tearing defects in castings [14],

as well as studies of Ny sensitivity to [15]:

- selection of a moment of performing Ny calculations, meaning corresponding temperature $T_{liq\text{-}sol}$ of the liquid-solid state – fraction of liquid phase LF_{Ny}, e.g. 0,01 (1%) or 0,03 (3%),
- type of the applied simulation code,
- material parameters in a database of a simulation code,
- density of a mesh.

On the basis of the above mentioned literature, it can be summarized that it is acceptable to use the Ny criterion calculation procedure for practically any alloy. Along with presentation of examples of such applications, it is also underlined, that there is a need of experimental validation studies with use of simple test castings. Putting together results of the NDT (Non Destructive Testing) and values of the Ny criterion allows determination of boundary values Ny_{crit} of this criterion for each case of an alloy. An important preliminary condition is a positive result of energetic validation, being a confirmation, that the databases used in the pre-processing of an applied simulation code correspond with the real conditions of the casting-mold system. It also pertains to the boundary and the initial conditions. Selection of a value is also of arbitrary character (mostly in range of LF_{Ny} = 3% to 1%).

Influence of mesh type, level of refinement and type of a simulation code are relatively less significant.

Simultaneously, it is difficult to find any information about use of the Ny criterion for cast iron castings in literature (formally, this procedure is available, just like for the other alloys). This problem was mentioned in papers published by the team of the author [16,17].

The experimental work done in various European foundries, in period of 1991-95, put together and described in [17] was about cast steel and nodular cast iron castings of average and high massiveness. A thermal analysis of the casting-mold systems was performed and internal defects of the shrinkage origin were identified using non-destructive testing methods (ultrasounds, radiography) and a penetrative method after cutting the castings.

In castings of plates of thicknesses between 75 and 150 mm, out of nodular cast iron GJS 400-15, cast without risers, porosities were found in central regions, more visible for the plates of smaller thicknesses. Simultaneously, for castings of cylindrical shape out of the same cast iron grade, with diameters between 75 and 200 mm (without risers), no discontinuity defects were found in area of the thermal axis, only some insignificant concavities on upper surfaces. Some of the mentioned studies were also used for validation of the post-processing procedures, for prediction of shrinkage defects in castings.

In summary of these studies [16], it was found, among other things, that boundary values of criteria, such as the Ny, proposed in literature, as well as moment of their calculation (for the selected temperature or fraction of liquid phase LF_{Ny}) should be strictly related to the type of an alloy, shape of a casting and interpretation of a notion of an “acceptable defect”, referring to threshold of detectability of defects during the quality control.

This paper undertakes this problem as continuation of studies started and described in [16], this time with application of a test casting in form of cylinders, Ø200x300mm, connected with a neck of 70x70mm, out of GJS 400-15 cast iron.

4. Experimental studies and results

A sequence of photographs presented in Fig. 3 and 4 illustrates selected stages of experimental studies, starting with presentation of models of castings, to results of the UT (Ultrasonic testing) and PT (Penetrating testing).

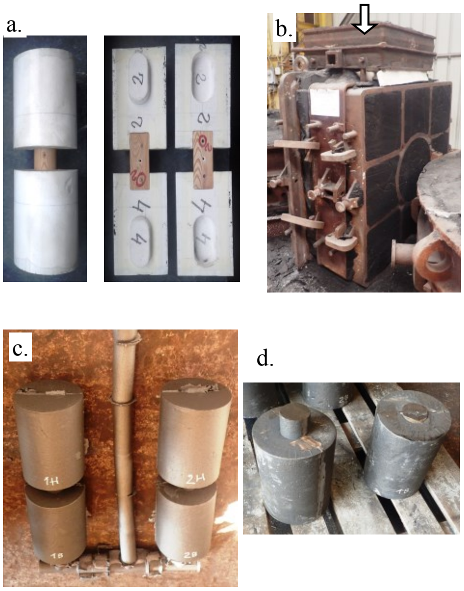

Fig. 3. Stages of studies in industrial conditions: a – patterns (Ø200x300mm) adjusted to molding without convergence on cylindrical surfaces of castings, b – a mold prepared for pouring (vertical mold joint), c – a raw casting removed from the mold, d – the casting after cut, prepared for NDT

Describing Fig. 4, it must be added, that it presents only examples of results of ultrasonic and penetrating testing. Full documentation of tests, conducted very thoroughly by independent NDT specialists with III. degree certification, unequivocally confirmed lack of shrinkage discontinuities in all parts of the test castings.

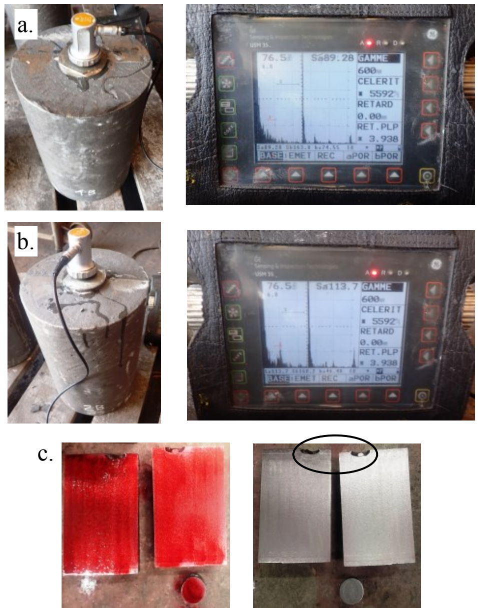

Fig. 4. Studies of presence of discontinuities in a test casting using the UT method (Ultrasonic testing)
a – upper part, b – lower part (velocity of ultrasonic wave = 5592 m/s, string back wall echoes without defect indication).
c – confirmation by a negative result of PT (Penetrating testing), after application: left – penetrating agent, right - developer agent, also without any defect indication. Minimal concavity marked (of open pipe shrinkage type)

This observation indicates, that in cylindrical castings of a compact shape and a thick wall, made out of ferritic nodular cast iron, evident axial zones of porosity are not formed. In author’s opinion, this should be related to the overlapping shrinkage phenomena of an austenite envelope and compensative expansion of graphite nodes. They occur, as it is known, in different conditions than in the gray cast iron (a case of the so-called specific eutectics). However, presence of a relatively rigid mold (furan sand), supported with a mechanism of interaction of ongoing solidifying cylindrical layer, helps for this particular shape of a casting. Such a hypothesis can be made, also on the basis of studies described in [16], where only test castings in shape of plates always indicated discontinuity defects (central porosities of shrinkage origin).

A question was asked – to what degree it is possible to recreate results of the above mentioned experiment using an available simulation code (the NF&S system was used [18]) and analysis of simulation results in form of parameters such as shrinkage and the Niyama criterion (post-processing activities).

5. Simulation study and results

To properly direct the simulation studies, in the beginning of this chapter, a reference to a diagram must be made (Fig. 5) [11]. This diagram illustrates philosophy behind a relation between predictions of discontinuity defects of shrinkage origin with local values of the Ny criterion, available for the analysis in the NovaFlow&Solid code [I]. The Ny criterion is named as a shallow criterion in [11], meaning that it concerns the solidifying layer, in which amount of the liquid phase LF is arbitrarily assumed (usually LF_{Ny} stays within range of 0,01 to 0,1).

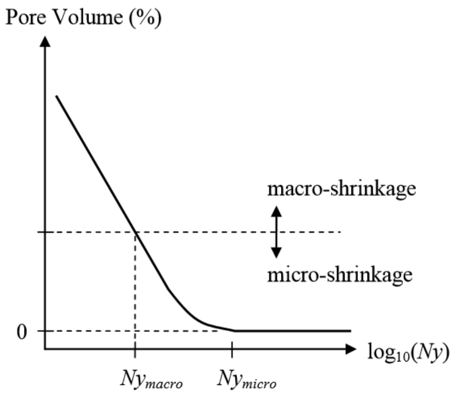

Fig. 5. Qualitative correlation between Ny (Niyama criterion) and shrinkage porosity [11]

Interpreting a relation resulting out of Fig. 5 and a commentary contained in [11], it must be observed, that:

- the Ny axis expressed in logarithmic scale may indicate, according to [11], a wide range of value of the Ny criterion,
- the Ny values above Ny_{micro} indicate, that locally material of a casting does not contain any discontinuities,
- the Ny values from the range of $Ny_{macro} - Ny_{micro}$ indicate, that decrease of the Ny below the Ny_{micro} is related to increase of chance of detection of the micro-shrinkage porosities using the RT methods (radiographic testing),
- starting from the Ny values less than the Ny_{macro}, the shrinkage porosities are evidently detectable with the NDT methods and the destructive methods.

Studies on cast steels and Ni alloys, described in [11], allow to observe, that values of Ny_{macro} stay within range between 0,1 and 1,0 $(K{\cdot}s)^{1/2}$/mm, while Ny_{micro} values – in range between 2 and 3 $(K{\cdot}s)^{1/2}$/mm (calculations performed for LF = 0,1). What is the conclusion? The critical Ny values (Ny_{macro} and Ny_{micro}) are contained in certain ranges and they always should be referred to results of a real experiment. In reference to a unit used by Niyama, the values are 0,129 to 1,29 $(K{\cdot}min)^{1/2}$/cm and 2,58 to 3,87 $(K{\cdot}min)^{1/2}$/cm, respectively. This fact, meaning the conversion factor from the original unit $(K{\cdot}min)^{1/2}$/cm [1] to the unit currently preferred in publications – $(K{\cdot}s)^{1/2}$/mm – is not always taken into consideration.

In view of the above mentioned information, a scenario of simulation studies of solidification of a test casting (identical as in the real experiment) was determined, using the same data for the calculations, except for variability of the cast iron density, ρ=f(T) (Fig. 6). As such:

- ρ=f(T) from the basic database of NF&S,
- ρ=f(T) variability obtained from validation in [5],
- ρ=f(T) – hypothetical linear variability of density.

The Figures below present juxtapositions of simulation results in three groups, referring to three variabilities of the 400-15 cast iron density (Fig. 6). The Shrinkage and Niyama criterion results are illustrated in Fig. 8 to 11.

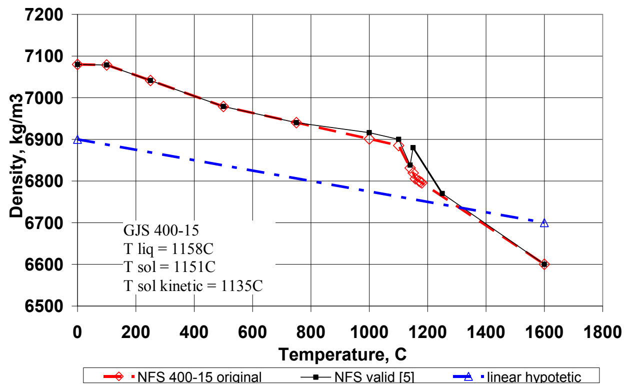

Fig. 6. Density variations as a function of temperature tested during the simulation study

Fig. 7 presents 3D geometry of the casting-mold system, corresponding to an experiment in real conditions, as well as a rule of realization of comparative analyses of prediction results for the shrinkage discontinuities (as Shrin) and the Niyama criterion (as Ny).

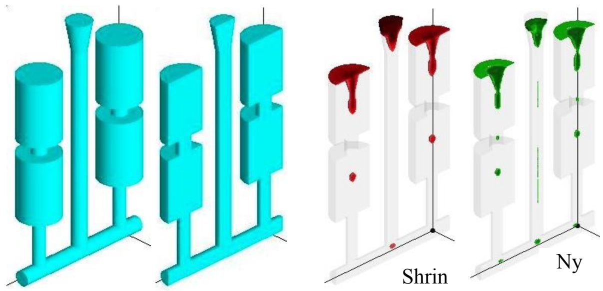

Fig. 7. CAD 3D geometry of test castings and presentation of location of predictions of the shrinkage defects (Shrin) and the critical zones of the Niyama criterion (Ny)

Each group was analyzed also by influence of moment of the Ny calculations, resulting out of current value of the LF_{Ny} fraction in the solid-liquid zone. In parallel, an influence of critical fractions of the liquid phase (CLF_{up} and CLF_{down}), controlling in a virtual dimension, referring to feeding in the solidifying area of an alloy ($T_{liq} - T_{sol}$), on predictions of the Shrinkaage and th criterion Niyama , was tested.

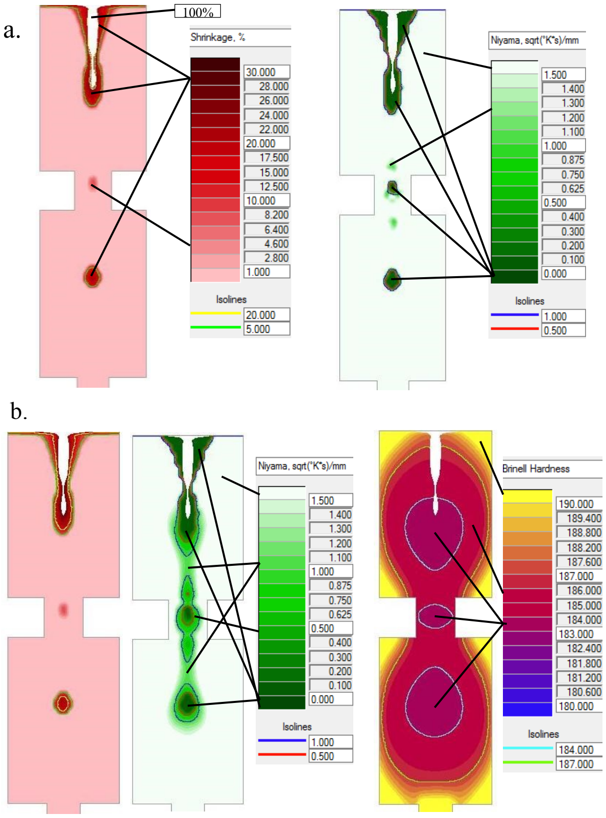

Fig. 8. NF&S predictions regarding central section of a test casting with use of NF&S database, where: CLF_{up}=70, CLF_{down}=30. a – Ny for LF_{Ny}=3%, b – Ny for LF_{Ny}=25%.

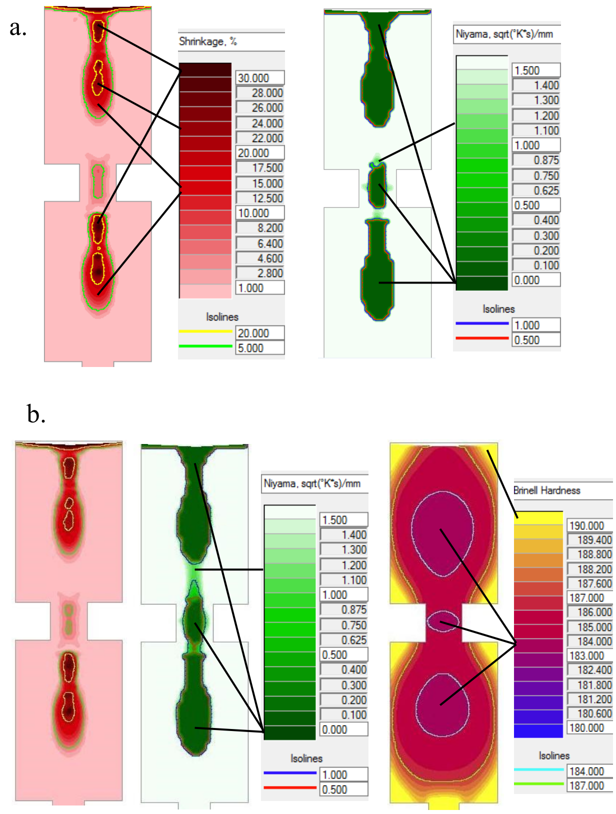

Fig. 9. NF&S predictions regarding central section of a test casting with use of NF&S database, where: CLF_{up}=95%, CLF_{down}=90%. a – Ny for LF_{Ny}=3%, b – Ny for LF_{Ly}=25%.

Parameters being present in the original database of the NF&S 6.0 code were a starting point (Fig. 8a). The obtained image of the shrinkage defects, especially the pipe shrinkage, definitely does not correspond with results of the experiment. As seen in Fig. 8b (Ny calculation for FL_{Ny}=25%), value field of the criterion Ny<1,5, in comparison with Fig. 8a (Ny calculation for FL_{Ny}=3%), comprises a larger area around the thermal axis of the casting. At an earlier stage, in a sense of advancement of the solidification process (liquid phase amount FL_{Ny}=25%), the calculated Ny criterion indicates a zone of endangerment with the shrinkage discontinuities, compatibly with an intuitive estimation.

Moreover, as results from presence of the pipe shrinkage, assumption of existence of the mass feeding up to CFL_{up}=70% and the capillary feeding CLF_{down}=30% is too enthusiastic for the GJS 400-15 cast iron. This was also questioned in studies by the team and described in [5]. Therefore, simulation studies were conducted for the boundaries of the mass feeding CFL_{up}=95% and the capillary feeding CLF_{down}=90%, on the basis of studies presented in [5] – Fig. 9.

Results in Fig. 9 confirm blocking of the pipe shrinkage defect already on the level of FL=95% and, according to expectations, show dispersion of discontinuities below this value of FL. As in the previous case (Fig. 8), changing LF_{Ny} from 3% to 25% did not influence location and value of the Shrinkage area. However, also in case of this test, the predicted shrinkage defects (slight concavity and porosities on a maximal level of 30%) were still not confirmed in the experimental tests. Change of the LF_{Ny} from 3% to 25% influenced (just as in Fig. 8) the character of location of the critical zones where Ny<1,5, from "island" to "continuous".

Fig. 10 presents results of simulation calculations for the modified NF&S database, according to recommendations in [5].

Because of consideration of a compensative impact of the eutectic graphite expansion in course of variability of ρ=f(T) – NFS valid [5], further decrease of intensity of the shrinkage defects is observed. It is so because even after using this curve (ρ=f(T)), intensity and location of these defects were not enough compatible with the experiment.

The last act of search for directions of validation of the relationship ρ=f(T) was a hypothetical assumption, that using the "trial & error" approach, there should be at least one course found, which will be satisfyingly close to result of the casting experiment (Fig. 4). At this stage, linear variability of ρ=f(T) was proposed, as presented in Fig. 6.

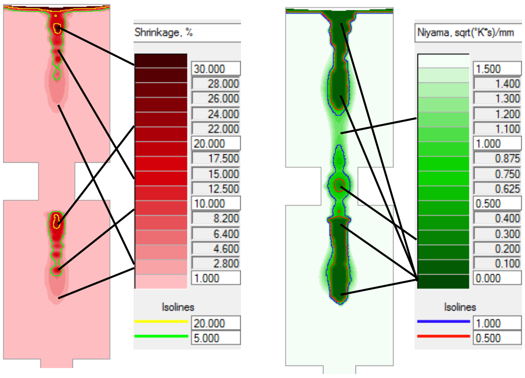

Fig. 10. NF&S predictions regarding central section of a test casting with use of AFE database developed in [5], including CLF_{up}=95%, CLF_{down}=90% and LF_{Ny}=25%.

For this option, the best compatibility with the experiment was achieved, with minimal shrinkage porosities (maximum of 4%). The same global effect can be achieved by introducing a variation ρ = f (T) with more effective shrinkage compensation illustrating the expansion of eutectic graphite. This image is overlaid with field of variability of the Ny criterion, which also contains values close to the critical zero (Ny=0), but these zones are less exposed. Referring to Fig. 5 – a hypothetical value of Ny_{min}, corresponding with a limit of detectability of the micro-discontinuity defects, in a casting out of the GJS 400-15 cast iron, may be on a level way above zero, e.g. Ny_{min} = 0,5.

Fields of HB hardness presented in three Figures: 8,9 and 11 are almost identical. It means, that the empirical relation for the HB calculation is referred to a local cooling velocity, so it is based on other premises than the criteria related to the front morphology (Ny is one) – there are no reasons to look for correlation between Ny and HB.

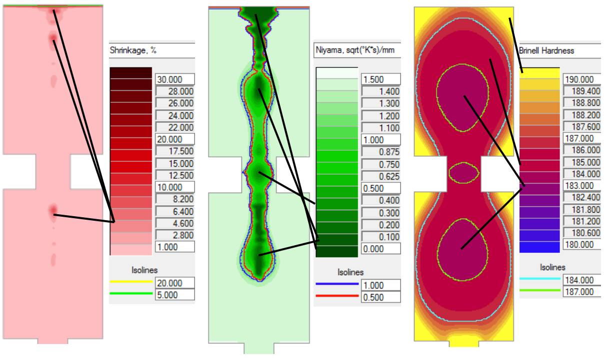

Fig. 11. NF&S predictions regarding central section of a test casting with use of AFE database developed in [5], considering modifications of ρ=f(T) (linear hypothetic), according to Fig. 6, with: CLF_{up}=95%, CLF_{down}=90% and LF_{Ny}=25%.

6. Summary

The paper presents an analysis of usability of a criterion, named after the first author of a publication from 1982 – the Niyama criterion (Ny). Only some authors undertaking this topic indicate a need for experimental validations of critical values of the Ny. The most commonly proposed methodology (RT studies) is not an obvious foundation for validating the Ny, because of unprecise threshold of detectability (in RT) in relation to the local values of the Ny_{micro}.

On the basis of the studies conducted in the paper, it can be recommended to treat both Shrinkage and Niyama parameters compatibly and with consideration of their variability during solidification of a casting. The problems mentioned in the paper were, among others, an influence of the density curve, a consideration of graphite expansion and an identification of morphology of the solidifying zone. Setting Shrinkage and Niyama parameter together should allow concluding about rightness of prediction of locally situated shrinkage porosities in castings out of nodular cast iron. It was proposed, to determine a map of values of the Ny criterion for the liquid phase fraction LF_{Ny}=25%. As it is known, on approximately this level of the liquid phase, the spheroidal eutectic cells cannot grow further without changing of their quasi-spheroidal shape. During this period, there is a strong interaction of the solidifying zone on the already solidified zones, and then on a mold of a given rigidity. This state of the solidification zone influences the thermo-mechanical balance of the whole casting-mold system. The Ny fields close to zero, calculated for the LF_{Ny}=3% are practically compatible with zones of predicted shrinkage porosity.

To sum up, the most recommended scenario of verification of rightness of the simulation predictions of the shrinkage porosity presence in a casting is experimental validation, referring to a correlation between an experiment performed in real conditions and a virtual experiment. A fact of undetected discontinuities, even with use of the PT, does not mean that in the zones, where Ny <1,5, there is a compactness (in the sense of soundness) identical as in the solidifying zones closer to the mold. If microporosities are impossible to detect with available NDT methods, the only way of verification are metallographic studies of microsamples, cut out of various zones of a casting, including examination of the cross sections.

Acknowlegements

The presented research results, were cofunded with grants for education allocated by the Ministry of Science and Higher Education in Poland (PUT - 02/25/DSPB/4312) and supported by R&D division of CIC Ferry-Capitain French Metallurgical Group.

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