Selected Principles of Feeding Systems Design: Simulation vs Industrial Experience

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Abstract

Simulation software dedicated for design of casting processes is usually tested and calibrated by comparisons of shrinkage defects distribution predicted by the modelling with that observed in real castings produced in a given foundry. However, a large amount of expertise obtained from different foundries, including especially made experiments, is available from literature, in the form of recommendations for design of the rigging systems. This kind of information can be also used for assessment of the simulation predictions. In the present work two parameters used in the design of feeding systems are considered: feeding ranges in horizontal and vertical plates as well as efficiency (yield) of feeders of various shapes. The simulation tests were conducted using especially designed steel and aluminium castings with risers and a commercial FDM based software. It was found that the simulations cannot predict appearance of shrinkage porosity in horizontal and vertical plates of even cross-sections which would mean, that the feeding ranges are practically unlimited. The yield of all types of feeders obtained from the simulations appeared to be much higher than that reported in the literature. It can be concluded that the feeding flow modelling included in the tested software does not reflect phenomena responsible for the feeding processes in real castings properly. Further tests, with different types of software and more fundamental studies on the feeding process modelling would be desirable.

Keywords: Solidification process, Castings defects, Simulation software, Feeding flow

1. Introduction

Numerical modeling plays a very important role in designing of products and manufacturing processes since it allows reduction of number of workshop tests, resulting in remarkable reduction of production preparation times and costs. In foundry industry the mold filling and casting solidification processes are the main subjects of the computer simulation. The models and computational algorithms used in commercial software should be verified in practice. Calibration of the model parameters is often required and recommended by the software suppliers.

Typically, the simulation results are validated by comparison of the locations of shrinkage defects in castings of non-even wall thickness, i.e. with hot spots. However, it is generally recognized that the feeding ranges in castings of even thickness are limited, both in horizontal and vertical walls. The experimentally determined values are available in the relevant literature (e.g. [1-3] and the source publications cited there). A comparison between the feeding ranges in such elements, obtained from simulations with those predicted on the basis of industrial experience, is one of the goals of the present study.

Another problem, often ignored in assessment of correctness of the simulation software is the efficiency of feeders. During solidification of a casting the feeder also solidifies and only a fraction of its volume is utilised for compensation of the casting shrinkage. This feeder's feature is sometimes expressed either as its inefficiency ratio (required feeder's volume divided by the

volume of shrinkage of the casting) or simply by the necessary feeder's volume to casting's volume ratio. Different shapes of feeders have different efficiencies [1-3]. In the present work the necessary feeders' volumes obtained in simulations were compared with those based on industrial experience and published in the literature.

2. Methodology

Most of the tests were carried out for two types of alloys, exhibiting fundamentally different solidification morphologies, resulting in different patterns of shrinkage defects and feeding abilities.

The first one was a low carbon steel (about 0.26 C%), being a typical alloy exhibiting the frontal type of solidification, leading to concentrated shrinkage cavities. The other was popular Al-Si10Mg type aluminium alloy, exhibiting the volumetric type of solidification resulting in more dispersed shrinkage porosity.

In Fig. 1 characteristic distributions of shrinkage defects in horizontal plates with feeders, resulting from limited feeding ranges, are shown for the both types of alloys.
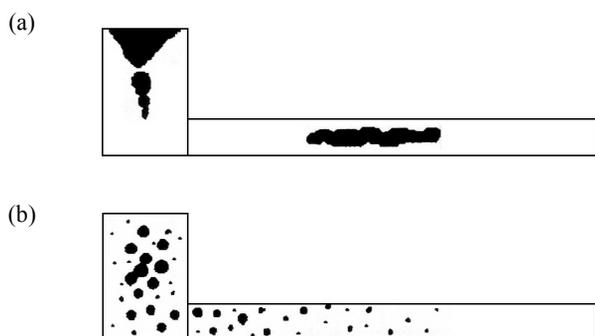

Fig. 1. Characteristic shrinkage defects due to limited feeding ranges in: (a) steel castings, (b) aluminium alloy castings [4]

2.1. Testing feeding ranges

Two geometries of square plate-shaped castings were assumed for all horizontal feeding range tests, of the following dimensions: 500x500x20mm and 1000x1000x20mm. All the risers were cylindrical with height-to-diameter ratio equal 1.5. The dimensions of the risers were calculated based on the two well known fundamental conditions, based on the feeder-to-casting modulus ratio and the volume ratio [4, 5]. The testing procedure always started from the number and arrangement of the risers resulting from the feeding ranges reported in the literature. In Fig. 2 an example of test casting with risers is shown.

Testing the feeding ranges in vertical elements was carried out only for steel castings because the relevant recommendations for aluminium alloys are not available. Six different geometries of vertical plates were used (height x width x thickness): 70x150x30 mm, 140x150x30 mm, 280x150x30 mm, 130x240x60 mm,

260x240x60 mm and 520x240x60 mm. On the top of each casting an open cuboidal riser was placed, dimensioned to satisfy the modulus and volume conditions. In vertical plate-shaped steel castings the porosity resulting from exceeding the feeding distance can be avoided either by adding extra side feeders or, more often, by padding additions increasing the temperature gradient. The maximum permissible heights of even thickness, based on the industrial experience for steel castings are given in [1]. All heights of the plates assumed in the present study were remarkably larger than those permitted by the literature recommendations [1] to be cast without additional padding or extra side feeders.
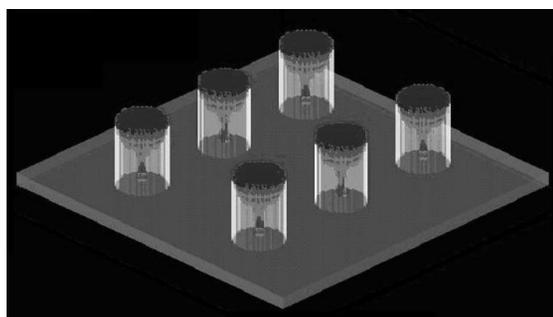

Fig. 2. Example of the plate-shaped casting with feeders used for testing the feeding ranges in horizontal plates

2.2. Testing efficiency of feeders

For relatively large volume, thin-walled castings, the riser dimensions found from the modulus condition must be usually increased in order to satisfy the volume condition:

$$V_f = x \cdot s \cdot V_c \qquad (1)$$

where V_f is the necessary feeder's volume, V_c is the casting volume (or its part which has to be fed from the feeder), s is the volumetric relative shrinkage of the alloy (resulting from cooling from the pouring temperature to the end of solidification) and x is the factor of the feeder's ineffectiveness. The latter expresses the ratio of the necessary feeder's volume to the volume of the expected shrinkage cavity (or porosity) in the casting.

This feature of the casting geometry can be quantitatively expressed by the following dimensionless shape coefficient [1]:

$$q = (casting\ volume\ to\ be\ fed) / (casting\ modulus)^3 \qquad (2)$$

The efficiency of risers can be determined only using geometries of high q values, i.e. where the riser dimensions calculated from volume condition are higher than those obtained from the modulus conditions. The test casting used in the present study was a horizontal plate of the following dimensions: 500x500x20 mm ($q \cong 5000$) with one, centrally located feeder.

Four types of open riser shapes were tested: cylindrical of the three height-to-diameter (h/D) ratios equal 1 and 1.5 as well as hemispherical ones, with bottom cylindrical neck. This choice

was motivated by the foundry practice and significantly larger efficiency of the hemispherical risers for steel castings, compared to the more commonly used cylindrical ones, as reported in the literature [1].

The testing procedure always started from the riser's dimensions resulting from the modulus condition. If a shrinkage defect was observed within the casting, then the dimensions of the risers were increased gradually, until the defect disappeared. The feeder's efficiency was calculated from the volume of the first riser which ensured correct feeding; however, the initial dimensions appeared to be satisfactory in some cases.

In the present study the efficiency (yield) of a feeder is defined by the reciprocal of factor x appearing in eq. (1), i.e. the ratio of the expected shrinkage defect volume to the necessary feeder volume, expressed in %:

$$Feeder\ efficiency = (s \cdot V_c) / V_f \qquad (3)$$

In the extreme case, when all the metal from feeder is utilized for casting shrinkage compensation (i.e. the feeder becomes empty after completion of solidification) then its efficiency is 100%.

The shrinkage values were found from the density curves of the alloys available from the software materials database, assuming default pouring (initial) temperatures, also applied in the simulations.

2.3. Simulation software and shrinkage modelling

In the present study the commercially available NovaFlow&Solid simulation software was used (research and educational version 2.92r15), by NovaCast Systems AB. The code utilizes the Finite Difference Method. The shrinkage formation and feeding flow modelling is based on the following assumptions.

The volume changes of the alloys are defined by their density vs temperature curves, covering the temperature ranges between pouring and solidus temperatures.

The flow of liquid or semi-liquid metal during solidification (i.e. feeding flow) and, consequently, the location of the shrinkage defects, are driven by two kind of forces: gravity and pressure gradients due to liquid volume change during solidification. The contributions of these two can be changed by the user, setting the value of the parameter called 'gravity influence'. The software allows choosing one of three levels of this parameter: "high", "medium" and "low". With increase of the gravity influence the location of the shrinkage defects moves upwards as the liquid metal tends to go down.

The partly solidified metal creates a resistance to the flow, dependent on the liquid phase fraction. Three ranges of this fraction are distinguished, in which different natures of the resistance and the corresponding governing laws are valid. These ranges have the following limits:

- 1 (beginning of solidification) and certain upper critical liquid fraction CLFu, called fluidity threshold;
- CLFu and another critical liquid fraction CLFd (<CLFu), called percolation threshold;

- CLFd and 0 (end of solidification).

Larger CLFu and CLFd values increase the flow resistance and reduce feeding.

Further details concerning the shrinkage and feeding model can be found in the help file of the software; the information can be obtained from www.novacast.se.

In the present study the above mentioned parameters, defining feeding flow driving forces and resistance, were set so that simulation results are closest to those predicted on the basis of industrial experience and recommended in the literature.

3. Results

3.1. Feeding ranges in plate-shaped castings

The results of numerical experiments oriented at finding the feeding ranges, both in horizontal and vertical plate-shaped castings were much surprising. In all simulations the castings revealed no shrinkage defects.

In Fig. 3 the extreme example of the results obtained in horizontal steel plates is shown.

(a)

(b)

(c)
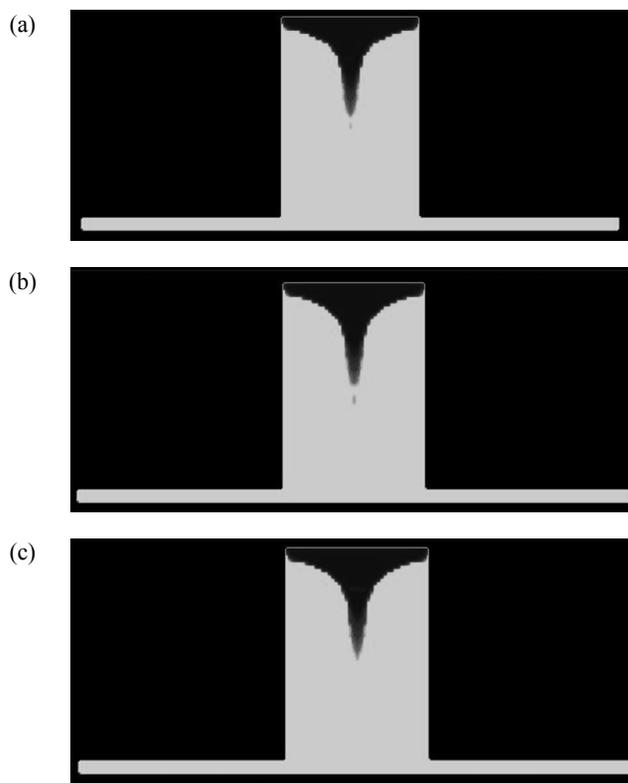
Fig. 3. Shrinkage defects obtained from the simulations of steel casting solidification, assuming CLFu and CLFd equal 0.9 and different gravity influence values: (a) – high, (b) – medium, (c) – low

The relative large dimensions of the feeder result from the large volume of the casting, according to eq. (1). Note that the

values of critical liquid factors were assumed here at the levels which nearly block feeding flow at an early stage of solidification and the distances from the feeder to the plate edges were several times larger than the sum of the end zone and the feeding range calculated from the literature data [1]. Similar results were obtained for different critical liquid factors values and all other geometries.

In Fig. 4 the similar extreme example of the results obtained in horizontal aluminium plates is shown. Although the shapes of the shrinkage cavities in the feeder are different from those obtained for steel, the fundamental result related to the feeding range is the same.

(a)
(b)
(c)
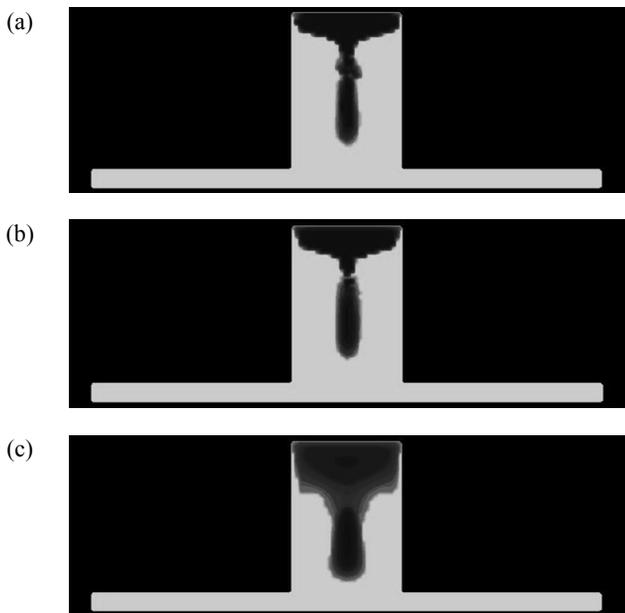
Fig. 4. Shrinkage defects obtained from the simulations of aluminium casting solidification, assuming CLFu and CLFd equal 0.9 and different gravity influence values: (a) – high, (b) – medium, (c) – low
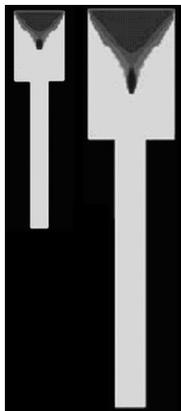
Fig. 5. Shrinkage defects obtained from simulations of steel casting solidification; the smaller plate dimensions (thickness x width x height, in mm) are: 30 x 150 x 280 (left) and 60 x 240 x 520 (right)

In Fig. 5 two examples of the simulation results obtained for vertical plate-shaped steel castings with only one top feeder are shown.

3.2. Efficiency of feeders

In some of the simulations carried out according to the plan presented in Section 2.2 the feeders' volumes resulting from the modulus condition appeared to be not large enough to avoid shrinkage defects in the castings. Typical examples are shown in Figs. 6 and 7.

(a)
(b)
(c)
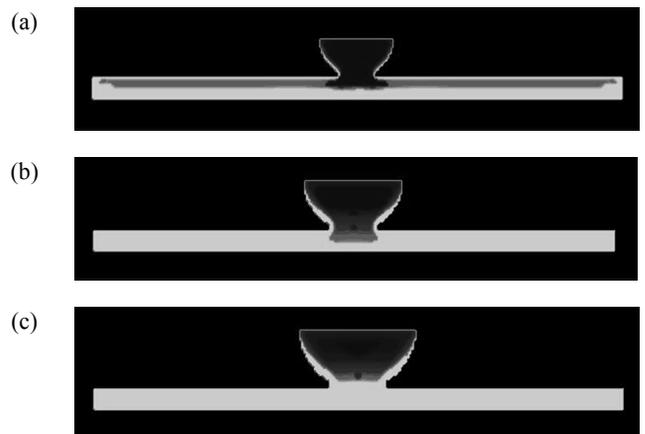
Fig. 6. Shrinkage defects obtained from simulations of steel casting solidification aimed at finding efficiency of hemispherical feeders: (a) – feeder dimensions resulting from the modulus condition, (b) – feeder dimensions increased insufficiently, (c) – satisfactory feeder dimensions

(a)
(b)
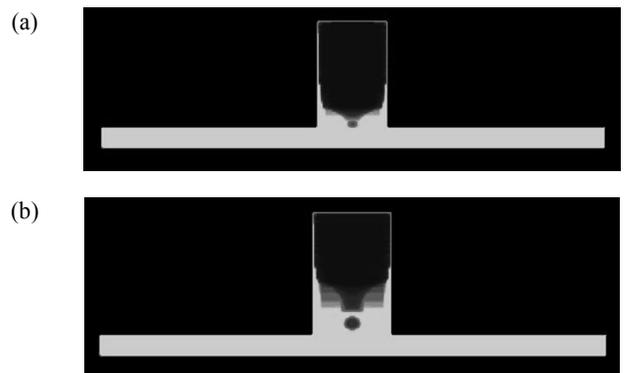
Fig. 7. Shrinkage defects obtained from simulations of aluminium casting solidification aimed at finding efficiency of cylindrical feeders (h/D=1.5): (a) – feeder dimensions resulting from the modulus condition (the shrinkage defect touches the casting area), (b) – satisfactory feeder dimensions

In some of the steel castings the feeders' dimensions resulting from the modulus conditions appeared to be satisfactory, as shown in Fig. 8. In such cases the efficiency parameter was

calculated from these feeder's dimensions and marked as "bigger then …".
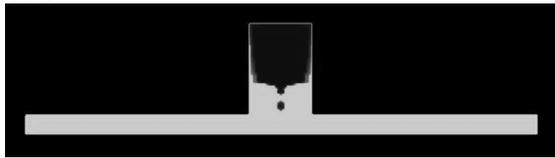
Fig. 8. Example of shrinkage defects obtained from solidification simulation of a steel casting aimed at finding efficiency of cylindrical feeders (h/D=1.5); the feeder's dimensions determined from the modulus condition permitted to avoid shrinkage in the casting in this case

In Table 1 all the feeder efficiency values found in the present study are shown, together with the values calculated from the literature recommendations based on industrial experience.

Table 1.
Efficiency of feeders found from the simulations (present study) and calculated from the literature recommendations

Cast alloy	Feeder type	Feeder efficiency from the simulations, %	Feeder efficiency from the literature, %	Ref. No.
Low carbon steel	Cylindrical h/D = 1	> 74	10	[1]
	Cylindrical h/D = 1.5	>71	10	[1]
	Hemispherical	56	16	[1]
Al based	Cylindrical h/D = 1	32	25	[2]
	Cylindrical h/D = 1.5	31	17	[2, 3]
	Hemispherical	23	N/A	

The general observation resulting from the values shown in Table 1 is that the feeder efficiencies obtained from the simulations are fundamentally higher than those resulting from the literature recommendations. This particularly concerns steel castings for which the corresponding efficiency values differ several times.

Another finding is that hemispherical feeders are less effective compared to the cylindrical ones, which is in contradiction to the literature recommendations [1].

4. Discussion of results

The numerical experiments carried out in the present study were aimed at comparison of the shrinkage defect distributions obtained from solidification simulations with those expected by the foundry experience. Two important issues were considered: feeding distances in plate-shaped castings of even thickness and effectiveness of risers, meant in terms of their yield. The general observation which can be made for the both problems is that the

feeding flow predicted by the investigated simulation software goes much too easy.

The problem of limited feeding ranges in horizontal and vertical casting walls of even thickness, often faced by foundry practitioners, is usually interpreted in terms of unsatisfactory temperature gradients in such elements. The well known Niayma criterion for steel [6] and Lee criterion for aluminium alloys [7] are useful and experimentally validated parameters defining conditions of proper feeding. It is important that these criterions include only temperature – related parameters whereas in the contemporary simulation software a big effort is made to model the feeding flow, taking into account the pressure field in solidifying casting. This is certainly a difficult task. In his famous book John Campbell [5] writes: "The development of computer software to predict the solidification of castings is not yet developed to predict the occurrence of porosity from first principles, i.e. calculating the pressure drop in the various parts of the casting, and thereby assessing the potential for nucleation and growth of cavities. This represents a Herculean task." It is symptomatic, that the software packages often include the option of calculation and displaying the distribution of the feeding criteria values (usually the Niyama criterion) as an alternative to the shrinkage porosity distribution resulting from the feeding flow modelling. This indicates that modelling feeding flow and porosity formation in solidifying castings is not considered as fully reliable even by the software authors.

The problem of feeder efficiency requires somewhat different approach. Unlike the feeding range, the discussion on this issue is rather modest in the literature. The fraction of the metal from the feeder which is utilized for compensation of the casting shrinkage, results from the solidification pattern of the feeder, i.e. mainly the cavity formation. In the fundamental work [1] the shapes of feeders' cavities are determined using a geometrical approach. In Fig. 9 a comparison of the typical cavity shapes assumed in [1] with those obtained from simulations is shown.
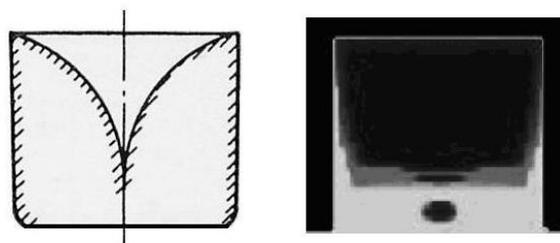

Fig. 9. Comparison of shrinkage cavity shapes in cylindrical feeders assumed in steel castings in [1] (left) with typical distribution of shrinkage defects in similar feeders obtained from simulations carried out in the present study (right)

It is clear that the efficiency of feeders resulting from the geometrical approach [1] must be much smaller compared to that obtained from simulations. Although the geometrical approach can be questionable, the recommendations concerning dimensioning of the feeders [1] have been successfully used by many steel foundries. For aluminium castings the differences between feeders' effectiveness obtained from simulations and calculated from the literature are much smaller then for steel castings. The recommendations for aluminium are based on

experiments and therefore they can be more realistic compared to Wlodawer's approach [1]. It is likely that the recommended feeders' sizes for steel castings are exaggerated.

5. Conclusion and further work

The substantial disagreements between feeding results obtained from simulations and the foundry experience can be certainly attributed to shortcomings of the feeding flow modelling utilized in the software algorithms. The diagnosis of the model flaws, indicating the necessary improvements, is a difficult task.

Obviously, comparisons between simulated and real experiments would be beneficial. However, one of the first and possibly easiest steps that could be taken is checking the relationship between simulated density or shrinkage defects distribution in plate-shaped castings and the temperature gradients, including Niyama and Lee feeding criteria. This would allow to analyse of feeding conditions in the test castings and would also facilitate finding possible inconsistencies within the software.

Another step would be to carry out simulations similar to those described in the present study, using other commercial software packages, such as MAGMASOFT or ProCAST. The available literature on feeding flow modelling, e.g. [8 - 10] suggests that the models utilized in some packages may be more complex and sophisticated compared to that used in the present work.

A practical conclusion resulting from the present study is that simulated feeding results, in the form of the density or shrinkage defects distribution, should be utilized with great care. The issues related to feeding flow modelling and shrinkage porosity formation in solidifying castings certainly require further studies.

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