Design of the Casting Technology using Foundry Simulation Codes – Development Condition

Paweł Popielarski[0000-0003-3797-5461] and *Dorota* Czarnecka-Komorowska[0000-0002-5027-7484]

Poznan University of Technology, Piotrowo 3 Str., 60-965 Poznań, Poland

Abstract. Simulation codes currently used in the foundry industry are primarily used to predict casting quality, quality tied mainly to the location of defects such as shrinkage (voids of shrinkage origin). The effective use of the simulation system requires identification and knowledge of, adapted to the reality, physical parameters (thermal) of the casting - mould system. The lack of as complete as a possible identification of these values, used in modelling dependencies, is the cause of limitation of the development and scope of models describing casting solidification. The development condition of the simulation code in the foundry practice is the correct model installation and the use of the database corresponding to the model. The following application presents the analysis of the impact of simulation parameters on the prediction of the casting defects.

1 Introduction

The casting of metals and alloys is a method of production of products, called simply casts, which gives wide possibilities of their geometric shape and simultaneous impact on their local functional features. The current global weight of casting production reaches 112.7 million tons [1].

The introduction of the alloy into the mould cavity is followed by a series of intense physical and chemical processes of interaction in a casting-mould system resulting from the heat shock, which the mould material is subjected to [2]. It is believed that the vast majority of the problems and casting defects take place in the period of filling the mould [3]. At the same time, however, there are wide possibilities of controlling the solidification and cooling of the casting, following the classic and/or special procedures provided for in the design concept of casting, possible to use for a given alloy, for a particular technology and in the function of the expected functional features resulting from the use of a cast.

In the classical approach for technology design, manufacturing of castings of good (assumed by the designer/user) quality, with the lowest possible amount of defects even below the threshold of, the so called, permitted defects following with the usual and today applied procedure, requires specimen castings to check (by means of control tests, including non-destructive testing on castings, their fragments, cast-on test bars) the effectiveness of this technology. Making specimen castings in the case of the assumed

correction of casting technology, increases the cost of production preparation and greatly affects the time for obtaining the first castings for the sale, which is of particular importance to the prototype castings, and especially single castings. Therefore, a rational procedure of optimization of the design of casting technology has involved the use of computer systems to support this process, also known in foundry as simulation codes. This is not to abandon the operation and quality control procedures. On the contrary, advanced principles of technology design and adherence to the principle of "tolerance of damage" [4,5] impose special requirements especially for non-destructive testing of castings [6,7] and at the same time become a permanent opportunity to support validation activities relating to computer systems. The concept of virtualization and validation are inextricably linked with the effective use of simulation codes.

2 Special condition of modelling of casting processes

With the development of microelectronics and the increase in computing power the mechanical engineering industry gradually introduced CAD / CAM systems in the field of machining and CAD / CAE programs to support design activities using of simulation [8,9,10]. Founding with aided design and manufacturing of castings was without doubt a pioneer in the area of simulation [11,12]. Simulation codes currently used in the foundry industry are primarily used to predict casting quality, quality tied mainly to the location of defects such as shrinkage (voids of shrinkage origin) [13,14].

Given the sequence of stages of the formation of the casting and the possibility of controlling its quality, modelling of the phenomena taking place during the casting solidification was the earliest issue in the theory and practice of metallurgy-casting. This modelling mainly related to the generation and heat flow is based on the model of the thermal energy dealing with thermal phenomena in a casting-mould system. It requires a proper, professional identification of thermo-physical parameters as input values (referring to casting, mould and the environment) that are necessary for these simulations (a component of certain conditions).

It can be stated that the primary purpose of modelling of casting solidification includes virtual generation of a description (in time and space) of movement of the division surface between the solid and liquid phase [15]. Describing the state of the surface, characterized by different development (known as the morphology of solidification/crystallization front) and taking into account the different dimensional scales of discretisation grid, the phenomena related to the mechanisms of the creation of various phases that make up the structure of the casting, assuming in advance the level of simplification of phenomena, can be introduced. Historically speaking, Rappaz [16] details the discretization scales of modelling, formally dividing them into four groups relating to four simulations (modelling) code generations, covering the aspects of crystallization and solidification of castings, namely the macro, meso, micro and nanoscales. In [17], he proposes three different criteria for the division of modelling scales. Unfortunately, most of the described models, included in, the so-called, multiphysics family, in terms of creating mechanisms and structure prediction, refer to the geometric modelling of local, i.e. very small, isolated areas, without reference to the whole casting [18]. E.g. only the single growth of equiaxed crystals is generated, or at most the growth of several crystals (dendrites), most often in 2D, out of context of actual conditions [19]. It cannot, therefore, bring expected by practitioners translation to the application even for ingots with a simple shape, not to mention castings of more complex shapes and larger sizes. Therefore, we must continue to search for effective solutions in the field of modelling from the area and Multiscale Multiphysics. These approaches show how to recognize the problem of simultaneous modelling of several

physical phenomena within the coupled models, including the alternate use of the scale of discreet distribution (macro-micro). The aim is an attempt to approach the complex reflection of the actual process. This, however, puts forward new tasks of validation, which must be taken up parallel with the creation of the models provided for coupling, not to mention the availability (or defining) additional parameters "operating" these new models (with a different degree of simplicity, and therefore the parameters that include in the simplification).

3 Methodology of validation of foundry simulation codes

The effective use of the simulation system requires identification and knowledge of, adapted to the reality, physical parameters of the casting-mould system. In this case, the user of code to master the phase of pre-processing, which is the best possible, corresponding to the actual casting-mould system, formulation of the model, which, along with the relevant differential equations also includes defined certain conditions (geometric conditions, the physical parameters of the casting-mould, initial and boundary conditions). The credibility of performed simulations depends on the reliability of these certain conditions, which unfortunately often is performed by users in a way too "automatic" (i.e., using the "setup - default") differing (due to lack of complete knowledge and experience of the user) from the real conditions of the system.

The proper use of the casting simulation code requires knowledge, a proper understanding and recognition of procedures to identify the parameters of the modeled thermal phenomena and an appropriate approach to their validation.

The sets of coefficients in publications [20,21], handbooks[22,23] and manuals are, for the users of simulation codes, the first source of acquisition of physical data formally needed for simulation calculations [24]. In the literature, there are papers on thermophysical parameters used in casting processes, concerning molding sands [25], cast metal-ceramic composites foams [26] and other materials [27,28].While singing them, the users should note that the coefficients as the research results presented in these sources were determined in conditions that were often not corresponding to the conditions of the actual time-temperature casting process (not going into details as to the type of alloy and forms). So one should pay special attention to the usefulness of the data used for the calculation and simulation methods and look for their completing and verification methods.The validation of each simulation code used in the foundry domain requires an individual approach due to its specificity. This validation can be elaborated based on experimental results or in particular cases by comparison the simulation results from different codes.

Only effective validation activities determine the actual usefulness of the simulation code to optimize the concept of casting technology. The scheme of classification of information sources for validation is shown in Fig. 1.
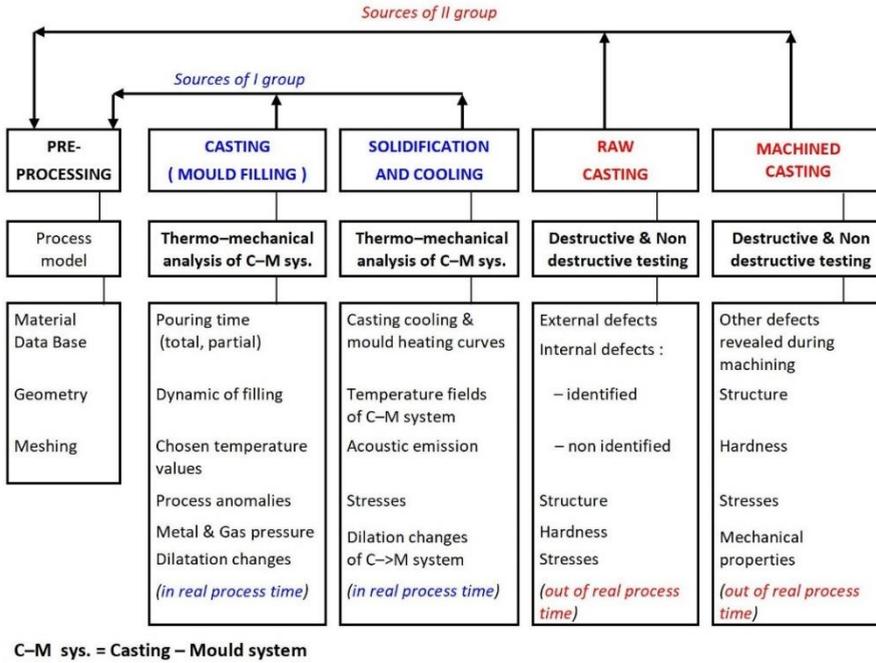
Fig. 1. Scheme of casting model validation. Sources and transfer of information in casting production.

The first validation step should always involve the adjustment of thermo-physical properties and the boundary conditions in the database of the simulation code to the actual conditions of the casting-mold system, to perform experiments based on thermal analysis of the real-time duration of the process (using sources of I group, Fig. 1). This type of validation is called validation of energy and should lead to revisions of the database made by the methods of solving inverse issues. Validation of material data determined in this way would necessitate simultaneous validation of the whole model (comparison of the results simulation and of real casting process, Fig. 2). However, the problem lies in the fact that this set of parameters obtained by the inverse solution should match dimensionally and geometrically in the sense of validation to the other castings, which always requires detailed analyzes.

The inverse problem solution for the cast iron solidification experiment in a sand mould is presented in Fig.3 and Fig.4. Results of experimental studies in form of cooling curves of castings and their derivatives, along with curves of heating in the mould are presented in Fig.4a. Based on the minimum of the first derivative, the plate solidification times were determined. Times of solidification were used to carry out the energetic validation.
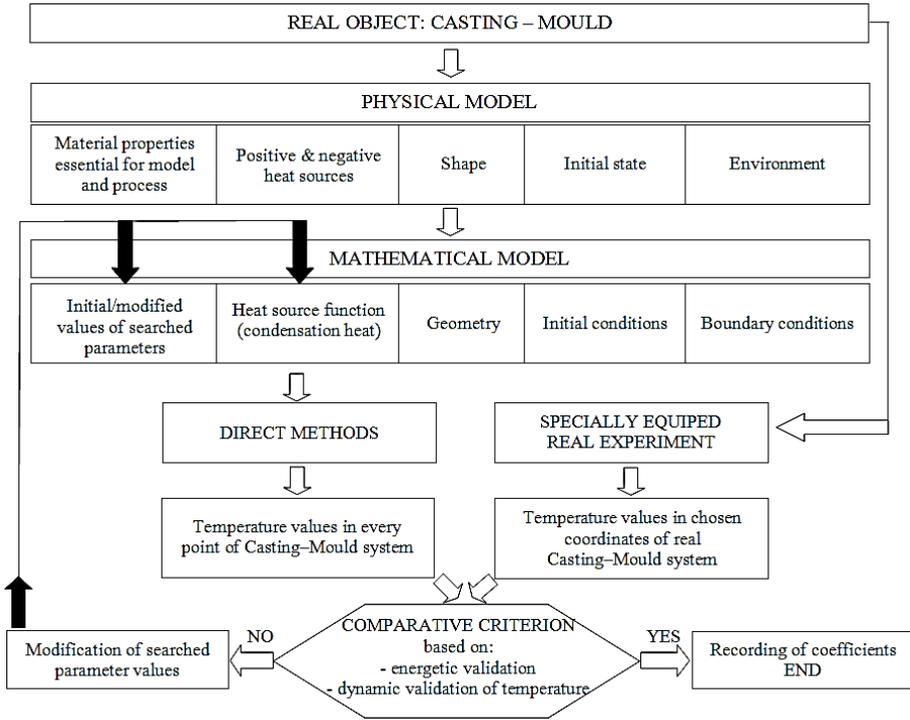
Fig. 2. Scheme of energetic/dynamic validation with the comparison criterion.

As a result of the validation studies, carried out according to the scheme shown in Fig.2, satisfying compatibility between curves from the simulation and the experiment was achieved. The results of the simulation are shown in Fig.4b. A good agreement between times of solidification in the experiment and the simulation was obtained. The values of obtained solidification times are shown in the graphs.

The second validation step takes place when a casting process is completed and include studies of selected features of the structure and quality of castings (using sources of II group, Fig. 1).

It is supposed that the uncertainty of thermophysical material data (in preprocessing) is associated with a lack of sufficient experimental data (sources of I group). This fact makes energetic validation difficult. In this case it is inferred that only one possible estimation of simulation quality results from the second set of data (sources of II group). The thermo-physical parameters determined based on the described validation procedure (in the first validation step) were used for a simulation of the casting process. The results of th simulation using the Procast code (forecasting of shrinkage porosity) were compared with the real casting are presented in Fig. 5.a.
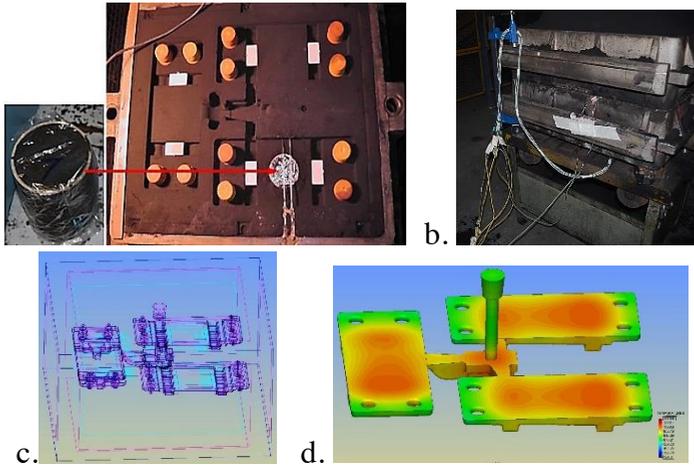
Fig. 3. Validation studies, a. Measuring core and mould instrumentation, b. experimental stand for cooling curves recording, c. 3D model of casting arrangement, d. simulation results.
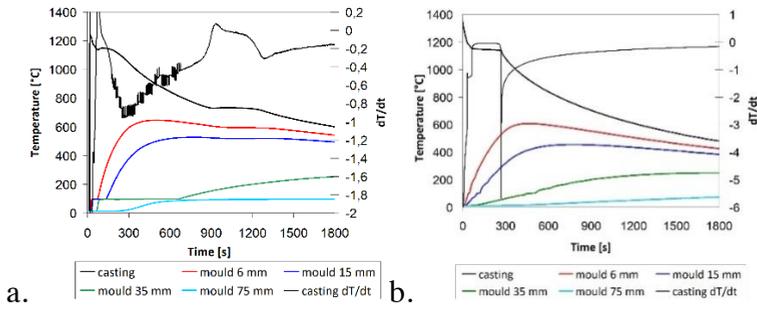

Fig. 4. Coolinga nd heating curves a. Results of the experimental studies, b. Results of the simulation studies.
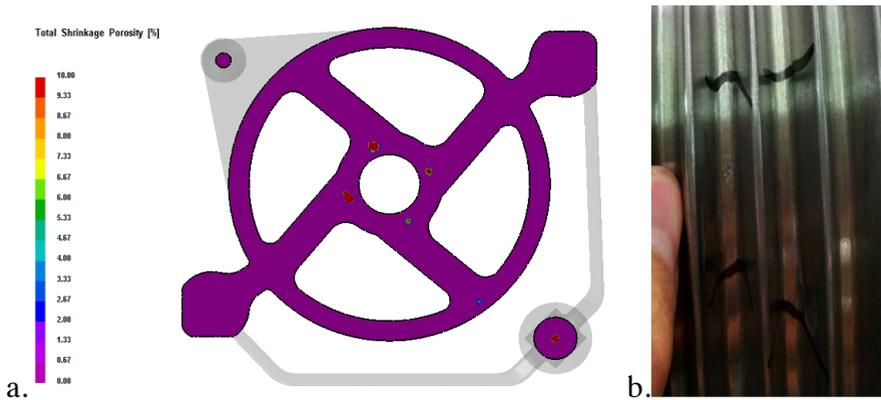

Fig. 5.a. Results of the simulation (shrinkage porosity) – Procast, b. shrinkage porosity visible on the real casting surface after machining.

4 Conclusions

In this study, the permanent need for simulation and experimental tests synergy which follow to improve confidence level to results of virtualization process of casting manufacturing was emphasised.

It was emphasized also, that the correctly prepared experimental validation supposes to be the only way to collect the knowledge and to supplement the database to regard the virtual properties map as close enough to reality.

Based on the obtained results of simulation calculations using the determined thermo-physical data of the mould sand are similar to the experiment results. A good compatibility of times of solidification of the plates castings was obtained (energetic validation condition was fulfilled). Also, a proper shape of heating curves was obtained from the simulation, in comparison with those recorded in the mould.

Well, the results showed, the issue of corrective modifications of material databases of each specific code of simulation introduced to the foundry remains one of the most important conditions for full use of the casting simulation codes.

References

1. Census of World Casting Production: A Modern Casting Staff Report.Modern Casting, December (2019).
2. P. Popielarski, Z. Ignasza: Effective modelling of phenomena in over-moisture zone existing in porous sand mould subjected to thermal shock. In: Delgado, J., Barbosa de Lima, A. (eds.) Drying and Energy Technologies, Advanced Structured Materials, vol. 63, pp.181–206, Springer, Cham (2016).
3. D. Hoefert: Quantify Casting Quality Through Filling Conditions.Metalcasting Industry Research. Inter Metalcast 14, 589–598 (2020).
4. R.I. Stephens, A. Fatemi et al.: Metal Fatigue in Engineering. J. Willey & Sons, Inc, (2001).
5. Z. Ignaszak, P. Popielarski, J. Hajkowski, J.B. Prunier: Problem of Acceptability of Internal Porosity in Semi-Finished Cast Product as New Trend – "Tolerance of Damage" Present in Modern Design Office. Defect and Diffusion Forum, 326-328, 612–619 (2012).
6. F. Herold, K. Bavendiek, R.R. Grigat: A new analysis and classification method for automatic defect recognition in x-ray images of castings. 8th ECNDT Proceedings, The eJournal of Nondestructive Testing Issue, 7, 10 (2002).
7. K. Gawdzińska, J. Grabian, W. Przetakiewicz: Use of X-Ray radiography in finding defects in metal-matrix composite casts. Metalurgija, 47, 3, 199–201 (2008).
8. M. Macko, A. Mroziński, J. Flizikowski: Design and Utility of Specialist Comminution Set-Up for Plastics and Organic Materials. 10.1115/IMECE2011-64155 (2011).
9. Z. Ignaszak, J. Hajkowski Contribution to the identification of porosity type in AlSiCu high-pressure-die-castings by experimental and virtual way. Archives of Foundry Engineering, 15, 1, 143–151 (2015).
10. M. Macko, A. Mroziński: Computer Aided Design of Wood Pellet Machines. In: Rusiński E., Pietrusiak D. (eds) Proceedings of the 14th International Scientific Conference: Computer Aided Engineering. CAE 2018. Lecture Notes in Mechanical Engineering. Springer, Cham (2019).
11. B. Ravi Computer-aided Casting Design and Simulation. STTP, V.N.I.T. Nagpur, July 21 (2009).

12. J.-D. Braun 1990/1998, huitannées de simulation de procédésenfonderie. Hommes et Fonderie, 282 (1998).
13. M. Jolly Casting simulation: How well do reality and virtual casting match? State of art. Review. Int. J. Cast Metals Res., 14, 303–313 (2002).
14. B. Ravi Casting Simulation – Best Practices. Transactions of 58th IFC, Ahmedabad (2010).
15. D.M. Stefanescu Methodologies for modelling of solidification microstructure and their capabilities. ISIJ, 35, 6, 637–650 (1995).
16. M. Rappaz Modelling of solidification at various length scales: From the processes to the microstructure and defects. EUROPAM, Mainz, October 16–17 (2003).
17. J.A. Dantzig Solidification Processes: From Dentrites to Design; Continuum Scale Simulation of Engineering Materials Fundamentals - Microstructures – Process Applications, Wiley-VCH (2004).
18. A.A. Burbelko, D. Gurgul, W. Kapturkiewicz, M. Górny Modelling of Eutectic Saturation Influence on Microstructure in Thin Wall Ductile Iron Casting Using Cellular Automata. Archives of Foundry Engineering, 12, 4, 11–16 (2012).
19. Q. Du, A. Jacot A two-dimensional microsegregation model for the description of microstructure formation during solidification in multicomponent alloys: Formulation and behavior of the model. Acta Materialia, 53, 3479–3493 (2005).
20. D. Czarnecka-Komorowska, T. Sterzynski, M. Dutkiewicz Polyoxymethylene/Polyhedral Oligomeric Silsesquioxane Composites: Processing, Crystallization, Morphology and Thermo-Mechanical Behavior. International Polymer Processing, 31, 5, 598–606 (2016).
21. Z. Ignaszak, P. Popielarski, T. Strek Estimation of coupled thermo-physical and thermo-mechanical properties of porous thermolabile ceramic material using Hot Distortion Plus® test. Defect and Diffusion Forum, 312-315, 764–769 (2011).
22. A. Goldsmith, T. Waterma, H.J. Hirschbaum Handbook of thermophysical properties of solid materials. ARMOUR Research Foundation (1961).
23. K.D. Maglie, A. Cezairhyan, V.L. Peletsky Compendium of Thermophysical Property Measurement Methods, Volume 2: Recommended Measurement Techniques and Practices. Plenum Press, London, New York (1992).
24. R. Sika, J. Hajkowski Synergy of modelling processes in the area of soft and hard modelling, MATEC Web of Conferences, 121, 4009 (2017).
25. P.K. Krajewski, J.S. Suchy, G. Piwowarski, W.K. Krajewski High Temperature Thermal Properties of Bentonite Foundry Sand. Archives of Foundry Engineering, 15, 2, 47–50 (2015).
26. K. Gawdzinska, L. Chybowski, W. Przetakiewicz Study of Thermal Properties of Cast Metal-Ceramic Composite Foams. Archives of Foundry Engineering, 17, 4, 47–50 (2017).
27. K. Grzeskowiak, D. Czarnecka-Komorowska, K. Sytek, M. Wojciechowski Influence of waxes remelting used in investment casting on their thermal properties and linear shrinkage. Metalurgija, 54, 2, 350–352 (2015).
28. D. Czarnecka-Komorowska, K. Grześkowiak, P. Popielarski, M. Barczewski, K. Gawdzińska, M. Popławski Polyethylene Wax Modified by Organoclay Bentonite Used in the Lost-Wax Casting Process: Processing−Structure−Property Relationships. Materials, 13, 2255 (2020).