The Conditions for Application of Foundry Simulation Codes to Predict Casting Quality

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Abstract. Casting processes are widely used to produce metal components wherein the cast iron castings represent more than 70% of the world production of castings. Designing a new casting technology requires incurring large costs associated with the preparation of instrumentation necessary to perform casting moulds. Therefore, the simulation codes currently applied in the foundry industry are used primarily to optimize the casting quality, quality mainly connected with the defects location such as shrinkage porosity. In this case, it is very important for the simulation code user 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 casting-mould, initial and boundary conditions). The lack of as complete as possible identification of these values, used in modeling dependencies, is the cause of limitation of the development and scope of models describing casting solidification - which sometimes translates into a foundry's negative attitude to the usefulness of the simulation codes, because of incorrect predictions on casting quality. Correct model installation and the use of a database corresponding to the model are the development condition of the simulation code in the foundry practice. The paper describes the utilitarian aspects connected with these problems.

Introduction

Casting of metals and alloys is a method of production, called simply casts, which gives wide possibilities of their geometric shape and simultaneously the impact on their local functional features, impossible to achieve in this area (on the sections of the walls) with other materials processing technology [1-3]. Conscious control of a structure, and thus functional features of castings, in particular for control of mechanical properties [4-6], is made possible by a synergistic linkage of theoretical and practical knowledge of metallurgical processes and different casting techniques in the context of application in practice.

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 in accordance with the usual and currently 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 in relation to the prototype castings, and especially single castings. Therefore, a rational procedure of optimization of design of casting technology has involved the use of computer systems to support this process, also known in foundry as simulation codes (hard modelling). Technology design using simulation codes is increasingly supported by soft modelling, i.e. the area of mathematical modelling based on empirical data set using artificial intelligence algorithms (Data Mining) [7, 8].

The place of simulation codes in the foundry industry

With the development of microelectronics and the increase in computing power in the 90s of the twentieth century, the mechanical engineering industry gradually introduced CAD / CAM systems in the field of machining and CAD / CAE programs to support design activities by means of simulation. Founding with aided design and manufacturing of castings was without doubt a pioneer in the area of simulation.

In the area of founding, systems based on geometric solid models used in foundries inevitably created conditions for the use of full virtualization of the casting process by technologists. A further significant increase in computing power favored the creation and proposing within the so-called up-grades, new modules, extensions of CAE systems, which gradually used algorithms based on new models of physical phenomena processes (the so-called hard modelling described by differential equations and soft modelling, using empirical formulas), which enabled getting a visual image of more and more phenomena that accompany casting. More and more advanced systems were used, such as CAE (simulation codes) ProCAST, QuickCAST, MagmaSOFT, NovaFlow&Solid, Simtec, Calcosoft, CastCAE, Vulcan and others, including increasingly more complex algorithms, numerical solutions using FDM (Finite Difference) and / or FEM (finite element). There was a gradual transition from the classical "paper" casting technology design to the more and more often implemented design technology with computer-aided casting which became a standard in foundry.

Simulation codes currently used in the foundry industry are primarily used to predict casting quality, quality mainly connected with the location of defects such as shrinkage (voids of shrinkage origin). Prediction of zones exposed to other casting defects (i.e. erosion of mould, the presence of non-metallic inclusions, zones exposed to "hot tears", to penetration of the mould by the liquid alloy) takes place on the basis of models - empirical formulas (called soft) or indirectly the user's knowledge and analysis of the results of simulation, for example, speed field of metal stream in the mould cavity or the time-temperature image of cast and mould interaction. These activities are the basis for decisions concerning the selection of optimal casting technology, with the expectation of obtaining the final, acceptable version of the concept, taking into account the criterion of the best relationship of quality / price of the casting. This made it possible to eliminate the classical method of *trial and error* commonly used over the years in the design process of casting technology, completed only through intuition of engineers and experimental tests [9]. While technologists with a simulation system and with the results of calculations using this tool, take decision on the basis of their assessment and based on the above, they suggest the next version after the change of technology / casting design or approve designed technology [9]. The simulation code is assumed to enable the verification of the (first or subsequent) technology concept and it is therefore necessary to have confidence in the quality of predictions analyzed in the framework of the so-called post-processing. The importance of professionally implemented experimental validation which increases the probability of forecasting accuracy and accumulation of knowledge on the subject should be reiterated at this point. The relations of validation and virtualization are an endless challenge and, to a large extent, they jointly decide about the success of the application code as a supportive tool.

The situation is different in the case of the thermo-physical parameters of cast alloy and mould and boundary conditions, where significant errors may appear, often resulting from the lack of material characteristics (thermo-physical) which are adequate to reality and simplifications used in the model, which, as already stated, critically affects the accuracy of a forecasting simulation. Deviations in the accuracy of forecasts are most commonly caused by material data mismatches in the conditions of production in the foundry. The problem of the sensitivity of the model to the errors of coefficients has been developed, among others, in [10-12]. The creators of casting simulation codes, as a principle (customary) do not take responsibility for the quality of the parameters contained in the database and at the same time they suggest modifications of material data provided there and supplementing the database with material parameters and the boundary conditions corresponding to the material and assortment conditions of casting in the particular foundry.

The problem of efficient defining and introducing certain conditions in the issues of modelling phenomena in the casting mould system

The simulation model contains a system of differential equations for solutions with the FDM finite difference method or FEM finite elements method and must also include certain properly defined conditions (geometric conditions, the physical parameters of a casting-mould system, initial conditions and boundary conditions). The credibility of simulation results depends on the credibility of these certain conditions.

It should be remembered that a number of responsible decisions related to defining and introducing certain conditions must be taken between the stage of defining the basis and assumptions for modeling and obtaining credible results (awareness of the influence of certain conditions on the margin of error of conclusion). Synergy of knowledge is consistently required, its usefulness is significant at any stage, including inter alia, the stage of creating and supplementing the material data base (the physical parameters of the casting-mould system) [9, 13, 14].

The effective use of a simulation system requires identification and knowledge of physical parameters (thermal) of the casting-mould system which are adapted to reality. The lack of as complete as possible identification of these values, used in modeling dependencies, is the cause of limitation of the development and scope of models describing casting solidification [1, 9, 15, 16], which sometimes translates into a foundry's negative attitude to the usefulness of the simulation codes, because of incorrect predictions on casting quality.

The sets of coefficients in handbooks and manuals are, for users of simulation codes, the first source of acquisition of thermo-physical data formally needed for simulation calculations [17-20]. While singing them, 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 data used for the calculation and simulation methods and look for their completing and verification methods.

Validation of a model is a condition absolutely required and necessary in view of the diversity of materials used for mould manufacturing. This validation is based on the effective adjustment of model components with parameters of processes occurring in reality and connected with the tests of different variants, which allows for the margin of error to be determined. This validation determines the usefulness of applying a simulation system for solving models and for optimizing casting technology. Validation of material data determined in this way would necessitate a simultaneous validation of the whole model (comparison of the results of simulation and of real casting, Fig. 1) [21]. In the case of thermal casting processes, such a procedure may be called a numerical identification of thermo-physical data. In the procedure of simplifying a physical model, it is important to take temperature–time conditions, simplifications of geometrical model and mesh design into account.

In conclusion, in order to assess the quality of available thermo-physical databases, the user must take into account their future purpose, and therefore consider the following issues:

- the source and the conditions of determining thermo-physical coefficients, such as accuracy of their determination (if possible), a comparison with the time and temperature range characteristic for specific conditions of the casting process,
- criteria and selection of the best (according to the user's and / or consultant's of a foundry knowledge) data set to solve the problem,
- the sensitivity of simulation results (uncertainty) - assessed in the static and dynamic manner - to the dispersion of coefficients (resulting from errors), which is identifiable by the user by means of simulation tests [10, 11].

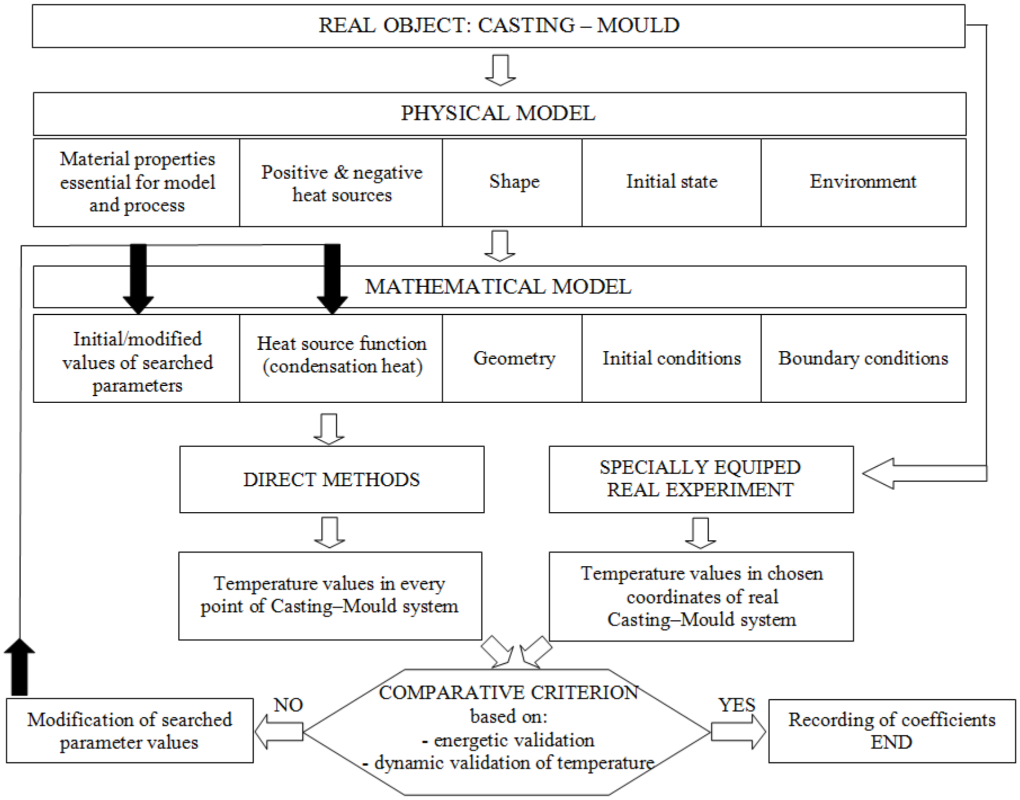

Fig. 1. Scheme of energetic/dynamic validation with the comparison criterion [21]

The problem of missing or unreliable coefficients in databases, essential for modeling processes, concerns not only the hard models (based on differential equations of elementary processes such as fluid and heat flows, diffusion, mechanical impact - stress), but also occurs in the case of the use of soft models (empirical equations including modeling of nucleation and grain growth, supply and the formation of shrinkage defects, local structures and their mechanical properties, expansion movements) [6, 22-25].

Initial conditions, which are one of the two remaining certain conditions, are relatively easier to identify and define, especially when the virtualization of a casting process includes the stage of pouring (it is enough to provide the temperature of metal stream entering the gating system). The last condition - the boundary condition, and actually boundary conditions - as they should be related to each pair of contacting elements of the casting-mould system - should be considered in terms of the significance of the effect of thermal resistance on the control surfaces (the problem of shrinkage slot variable in time) on weakening the heat flux in relation to the thermal resistance of the layers adjacent to the two surfaces in contact and resulting from the material thermos-physical parameters. Thus, for example, a correctly estimated value of thermal resistance is much more important and necessary to determine for the casting-metal mould contact than the casting-sand mould contact.

Casting process simulation

Modeling and simulation of complex phenomena during crystallization of alloys in the simulation codes are based on mathematical and physical models, which in different ways reflect the complexity of physical and chemical processes and their coupling. Simplifications they are subjected to are not in a sufficiently comprehensive manner disclosed to users in help windows and in manuals of codes. While developing the project of experimental validation of casting simulation codes, it must be assumed that the scope of these simplifications is assigned unambiguously to the code that is used. And, that this also applies to "soft" models within the compliance of virtual and actual result of simulation calculations, most commonly the predictions of porosity of shrinkage origin.

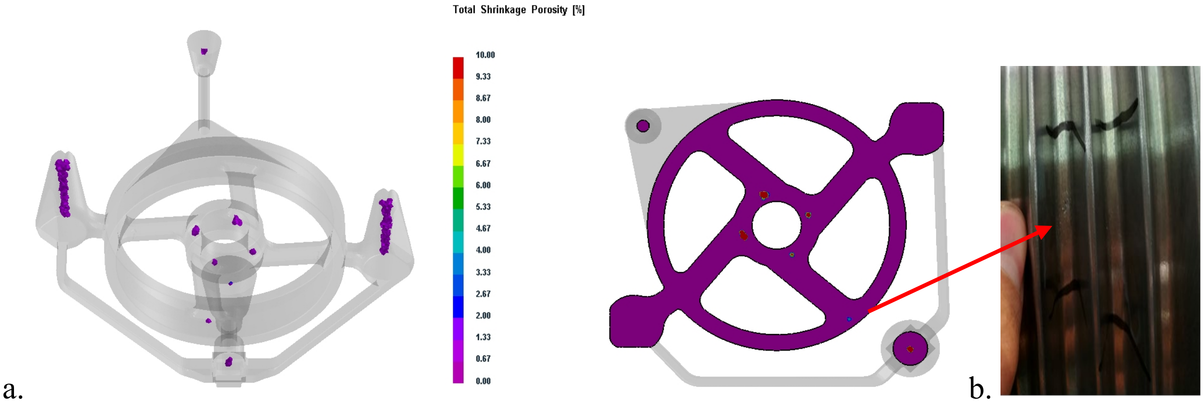

Fig. 2. Shrinkage porosity: a) results of the simulation – Procast, b) shrinkage porosity visible on the real casting surface after machining

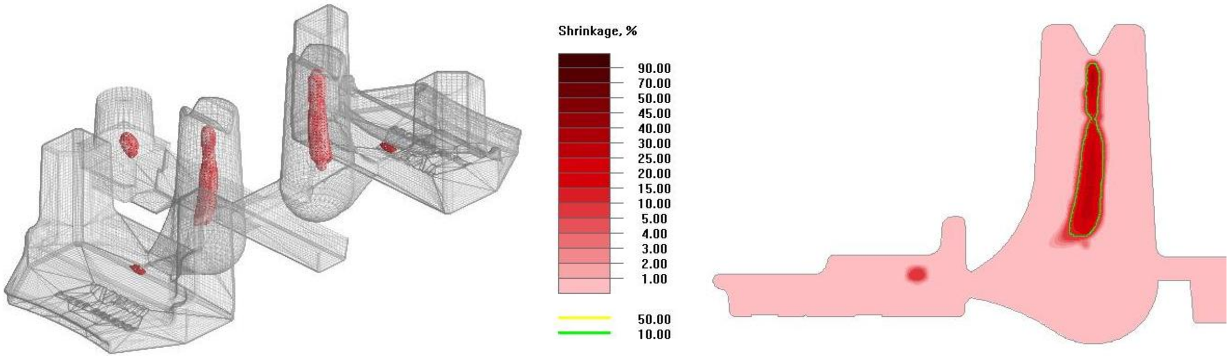

Fig. 3. Results of the simulation (shrinkage porosity) - NovaFlow&Solid

Thus, the basic expectation formulated by users (especially beginners) to process a virtualization system, as to confirm the effectiveness of pre-developed technology, is to check its correctness in terms of the exclusion of defects of shrinkage origin. Prediction of these defects and comparing them with the acceptance criterion formulated in the conditions of acceptance by the customer, is to admit the casting for the production (by initially developed and then corrected version of technology).

The thermo-physical parameters determined on the basis of the described validation procedure were used for a simulation of casting process. The results of the simulation using the NovaFlow&Solid and Procast codes (forecasting of shrinkage porosity) were compared with the real casting. The results of simulation are presented in the Fig. 2 and Fig. 3.

Conclusions

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

Only effective validation activities determine the actual usefulness of a simulation code to optimize the concept of casting technology. The first validation step should always involve the adjustment of thermo-physical properties and boundary conditions in the database of a 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.

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

The results concerning the applicability of the software and relevant material models obtained during the research should also be of interest to other technological areas in which there are thermomechanical issues, e.g. the production of protective coatings by ESD and laser machining [26-28], nanocomposite materials [29], hydraulics of heavy working machines [30] and related methods for the analysis of experimental results [31, 32].

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