Coupled Numerical Simulations of the SIMCENTER 3D for Casting Equipment Made of Grey Cast Iron

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***Abstract*—Since many years the global economy has been focused to constantly increase profitability. One of the ways leading to this goal is optimization. The optimal production process creates savings by reduction of labour, material usage, production waste or costs of poor quality. The product could be also optimized, by increasing performing parameters such durability, reliability or other specific useful features. Those days many methods of optimization is available, but the most advanced are based on the computing simulation, which are able to simulate processes and phenomena that apply to the product and allows applying its modification to maintain key parameters with reduction of cost of production. The article describes the process of preparation and running the simulation of ingot mould production process. Ingot mould is an element of a casting accessory, made of grey cast iron. Presented research was a part of a larger process aimed at extending the poured life by describing and simulating the phenomenon occurring in an element during its production and operation. The work carried in the Siemens Simcenter 3D environment and usage of the Multiphysics solver to perform coupled thermal and structural analyses.** [1]

***Index Terms*— coupled simulations, thermal simulations, stress simulations, casting accessory, foundry equipment, ingot mold, gray cast iron, Simcenter 3D, Siemens NX**

I. Introduction

Cast iron is defined as a high-carbon, foundry iron-carbon alloy. The carbon content here is greater than 2.0%, usually it ranges in the range of 2.0 - 6.7% [1]. Three basic types of cast iron can be determined from the iron-carbon balance system. Depending on the carbon content in the structure, cast iron can be distinguished: hypoeutectic (% C <4.30), eutectic (% C = 4.30) and hypereutectic (% C> 4.30). The eutectic value for 4.30% carbon content applies here to the iron-cementite system. For the iron-graphite system, this value is 4.26% [2, 3]. The metallic matrix of cast irons is usually perlite, ferrite or a mixture thereof. Sometimes there are also cast irons in the matrix of which cementite or non-metallic inclusions occur. Graphite precipitation is also a very important element of the structure of cast iron. Graphite, as a very soft material, causes, among others, a decrease in mechanical properties, reduces casting shrinkage, improves machinability of cast irons, increases their fatigue strength and suppresses mechanical vibrations. The PN-EN ISO 945: 1999 standard distinguishes 6 shapes, 8 types of size and 5 types of arrangement in the material. Alloy additives and impurities play a very important role in the process of crystallization and graphitization of cast irons. Elements facilitating the graphitization process are, for example, silicon, phosphorus, nickel, copper or aluminum, while elements such as manganese, molybdenum, chromium or sulphur make it difficult [2, 4].

Thermal-structural coupled analysis was performed in the ingot mold production simulation. This type of analysis is characterized the transient thermal analysis are carried out in the time step Ti and the results (temperature distribution) are the input data for the steady state structural analysis. The next time steps Ti + 1 are counted by giving a new temperature distribution which is the input for structural analysis. In addition, structural analysis takes into account the state of deformation from the previous step Ti. Finally, at the end of the analysis, two sets of results were obtained: the distribution of temperatures at designated times Ti and the distribution of deformations and stresses. The simulation is carried out in at least two time steps, covering the total time of the simulation. It was assumed, based on industry reference data, that the ingot mold cooled in the casting form for 3 days (260,000 s) [5, 6]. Every analysis step is defined by the following parameters: end time, time step generation option, temperature error tolerance, minimum time step, maximum time step and frequency of saving results [6, 7].

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In the simulations, an additional discretization process was used, which allows the analysed block to be turned into a series of smaller elements joined together in nodes. Deformations within one element are determined by shape functions and so linear elements are described by a linear function, while higher-order elements are described by a quadratic function. The size of the elements used is primarily responsible for the accuracy of calculations, therefore using a smaller size of the element allows to get more precisely results. More accurate results, however, causing extending the analysis time as well as increased consumption of cache memory (temporal) and mass storage (permanent). Below the grids of individual solids (Fig. 1).

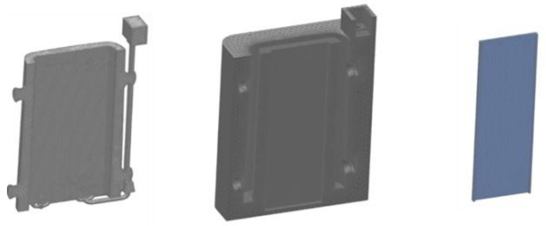

Figure 1. Meshing applied on solids – described method uses three separate solids formed into one system.

Discretized solids constitute three separate elements. Determining the interactions between solids at contact points will cause the three separate meshes will form one system in which interactions will occur. 10-node tetrahedral elements were used for discretization. The FEM model consists of 133,832 elements and 218,242 nodes. Fig. 4 shows the imposed ingot mold and mold.

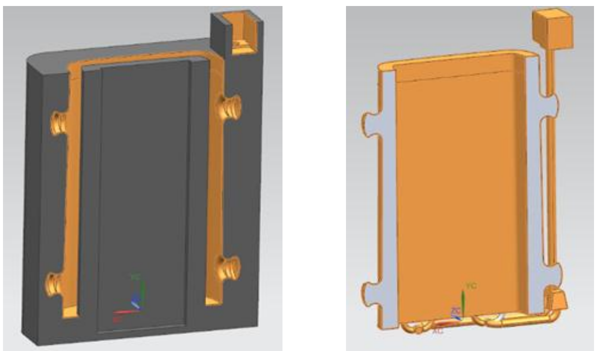

Figure 2. Solid merging process – solid No1 with Solid No2

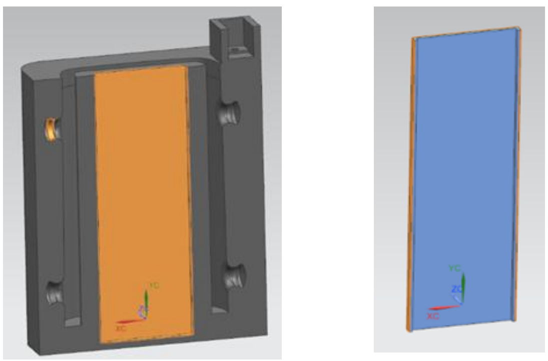

Figure 3. Solid merging process – solid No1+2 with Solid No3

II. RESULTS

Coupled analysis used two types of boundary conditions: thermal and structural. The first one refers to the initial data in thermal aspect, while the second type of conditions is related to the constraints of location and displacement. Firstly, thermal constraints and boundary conditions were described:

Initial temperature: this is the temperature that the object has at the time of analysis T0. The temperature is expressed in degrees Celsius. Fig. 5 shows an example definition of the initial temperature.

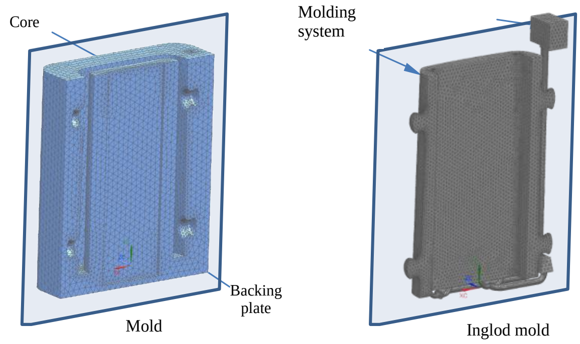

Figure 4. Mould and ingot mold mesh solids: 10-node tetrahedral elements.

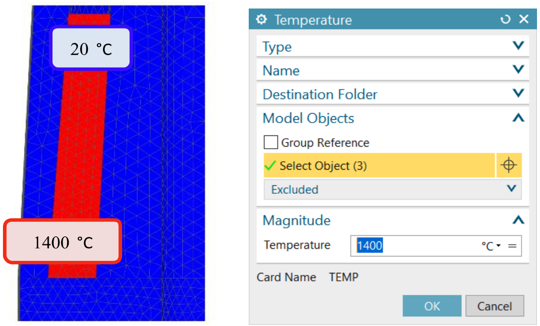

Figure 5. Initial temperature definition (right view of NX's dialog box)

Reference temperature: is the temperature against which the thermal material properties are calculated, thermal vapour (thermal contact) - This is a type of bond connecting two selected surfaces where the heat exchange between them is determined by the heat exchange coefficient. The unit of the heat exchange coefficient will be W/(mm^2*°C). Fig. 6 shows an example of heat vapour with a defined heat transfer coefficient.

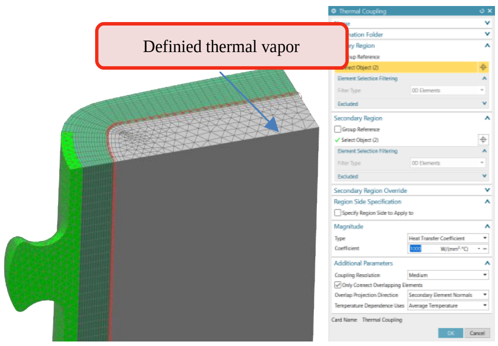

Figure 6. Thermal vapour definition with defined heat transfer coefficient.

Glue contact pair. It is a type of bond connecting two selected surfaces together where lossless heat exchange between the surfaces. Fig. 7 shows an example of a "glue" pair on the example of a sprue and ingot mold.

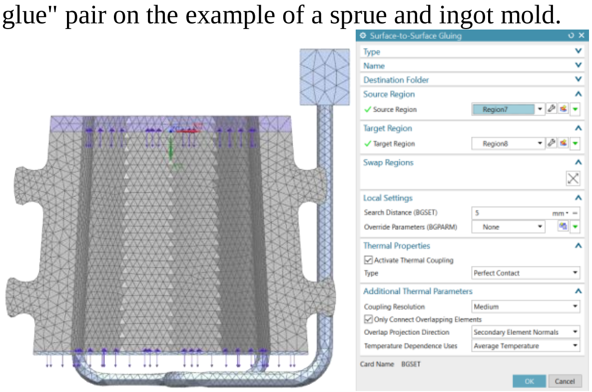

Figure 7. Glue contact pair on sprue and ingot mold.

Convection to the environment. It is a type of constraints determining the amount of heat emitted by free convection to the environment from a given surface. The unit of free convection will be W / (m2·°C). Fig. 8 shows the defined boundary condition on the free surface of the mold core to the mould.

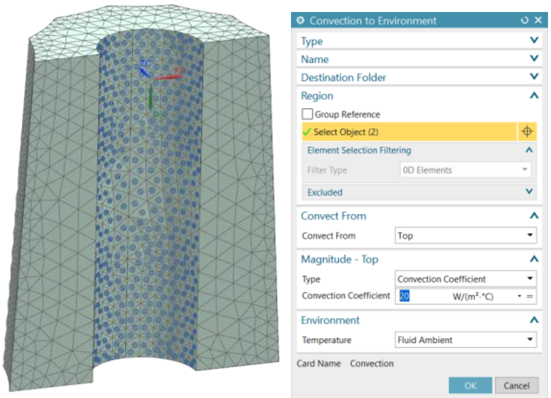

Figure 8. Convection to the environment defined boundary condition on the free surface of the mold core to the mould.

Radiation to the environment. It is a type of constraints determining the coefficient of emitted heat through radiation to the environment from a given surface. This factor is a dimensionless value. Fig. 9 shows the defined boundary condition on the free surface of the ingot mould core.

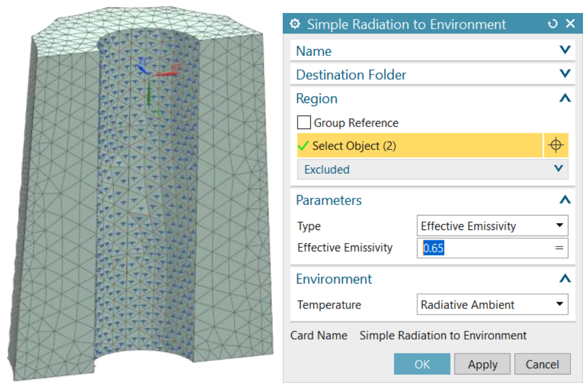

Figure 9. Radiation to the environment: defined boundary condition on the free surface of the ingot mould core

Thermal boundary conditions shown in Table I and schematically shown in Fig. 10.

TABLE I. THERMAL BOUNDARIES CONDITIONS

	Initial temp [°C]	Ref temp [°C]	Contact pair - heat transfer coefficient [W/(mm²°C)]	Horizontal convection [W/(m²°C)]	Vertical convection (down) [W/(m²°C)]	Vertical convection (up) [W/(m²°C)]
Ingot mold + casting system	1400	1400	1000	-	-	10
Mold	20	20		20	5	20

Boundary conditions for structural analysis are limited to constrain displacements in the model's symmetry plains and determining the reference temperature taken into account in calculating thermal expansion.

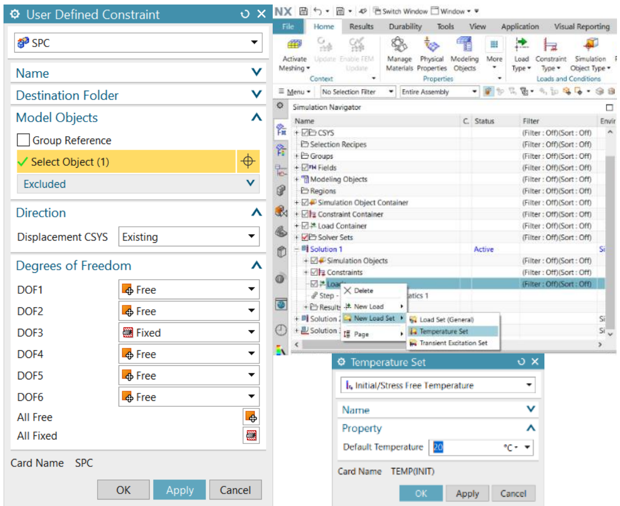

Figure 10. View on user definition constrains (left) and global temp set (right) to calculate thermal expansion.

As a result of the configuration of boundary conditions, casting simulation process was set.

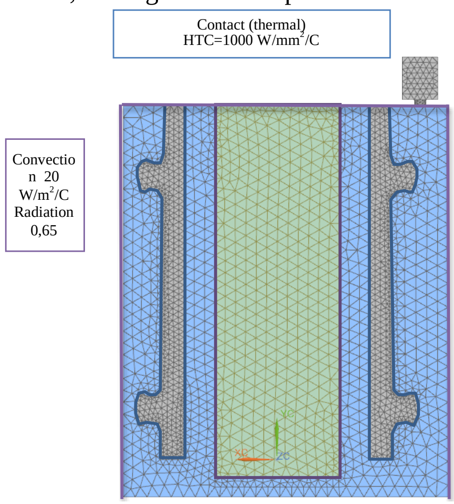

Figure 11. Boundary conditions scheme.

Simcenter allows to define customized material or user can choose it from database of materials available in the software's library. Required material's data for thermal and structural analysis:

- Casting: density, coefficient of thermal expansion, thermal conductivity, specific heat, Young's modulus, Poisson's ratio.

- Moulding sand: density, coefficient of thermal expansion, thermal conductivity and specific heat.

Simulation specific parameters are presented in the Table II.

TABLE II. PARAMETERS SET FOR SIMULATION.

Step	Solution Type	End Time [s]	Temperature Error Tol. [^{0}C]	Minimum Time Step [s]	Maximum Time Step [s]	Incrementation Type
1	Transient	1	5	1	1	Automatic
2	Transient	10,000	5	1	500	Automatic
3	Transient	86,400	5	100	4320	Automatic

Simulation results let to determine duration of the calculation of the ingot mould pouring simulation for 12 hours. In first step, 1 time point was generated, in the second step 20 time points, in the third step 10 time points. Result of the temperature course simulation are presented on Fig. 12.

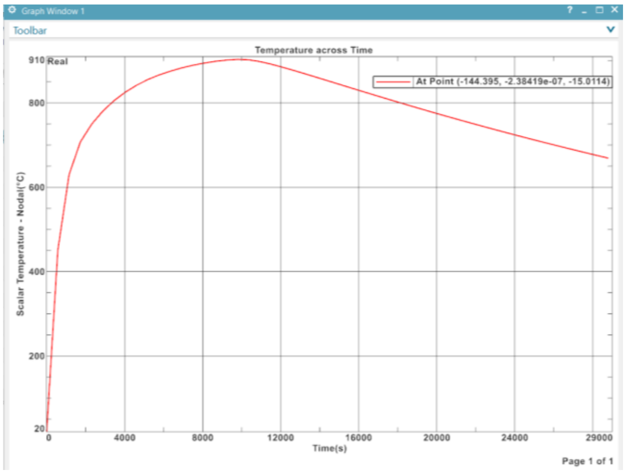

Figure 12. Results of temperature simulation, 24 hours of cooling time.

On Fig. 13 resented graph was crosschecked with results of measurements on a real object with a set of thermocouples, placed at selected points (sketch).

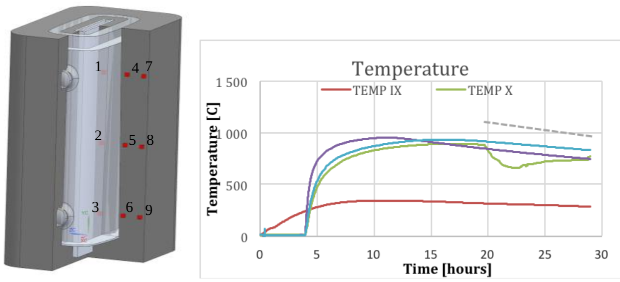

Figure 13. Thermocouples location at casting (left) temperature graph taken during casing process (right).

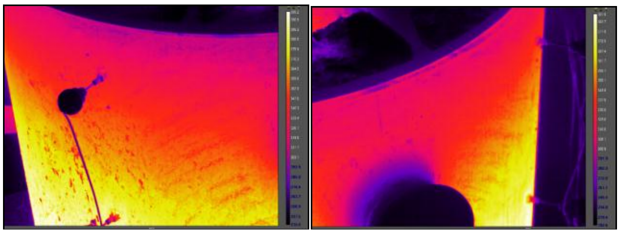

Figure 14. Picture taken by thermal camera during casting process of ingot mould. On left: attached thermocouple.

Based on the presented graph, compatibility of process variability can be observed. Measurement results will be used to verify and determine the calculation parameters and calibrate models for selected moulds. Simulation conditions verification allows to start the main part of the simulation related to stress values arising in the element during its casting. Ingot mould stresses graphs presented on Fig. 15-18, at t_{equal} 86000 seconds.

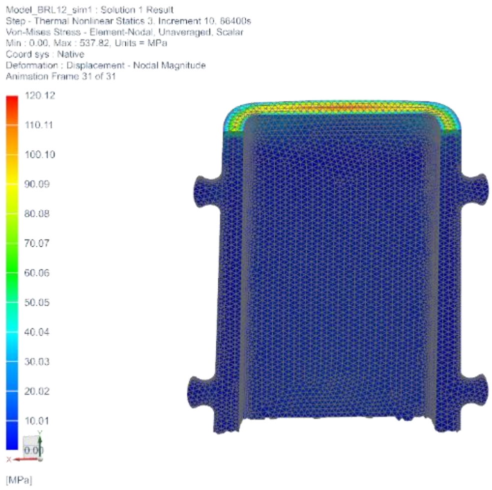

Figure 15. Map of reduced stress at t = 86400s

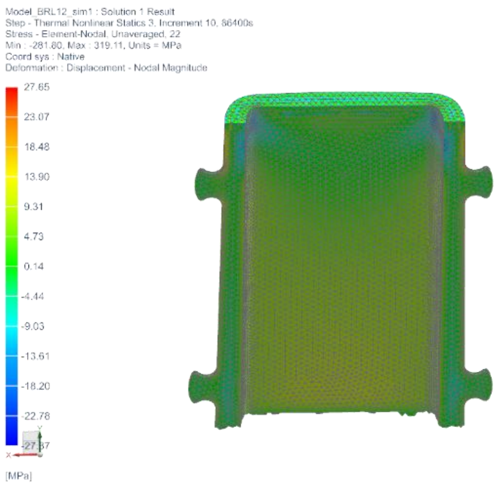

Figure 16. Y stress map at t = 86400s

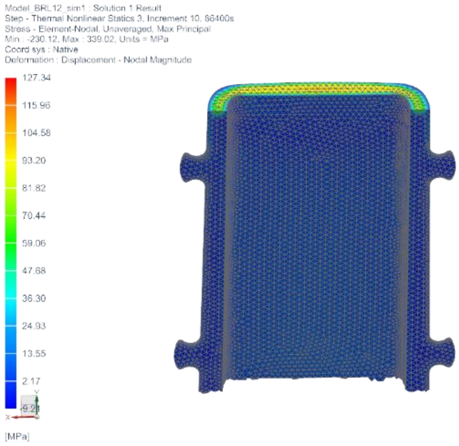

Figure.17. Map of S3 stress at t = 86400s

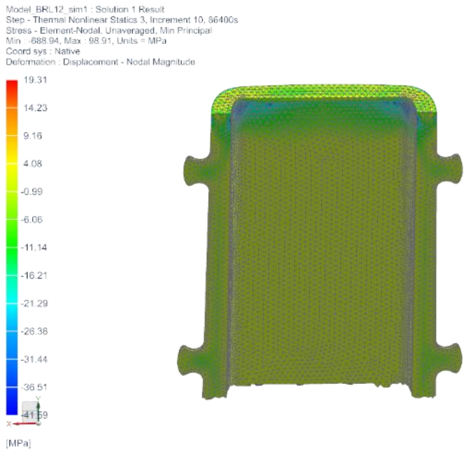

Figure. 18. Map of S1 stress at t = 86400s

III. Conclusions

As a result of the process of defining the boundary conditions of the simulation, solver selection, material and thermal parameters and mesh application, obtained results are match with results gets from physical object. Therefore it can be assumed that the results of stress simulations are reliable and correctly describing the phenomena occurring in the ingot mould. It will be the starting point for the next phase of the research project, aiming to map the phenomena occurring in the process of ingot work as a part of entire casting system.

The research program, whose goal is to increase the ingot durability, is based on the results of coupled numerical simulations where in the first iterative loop phenomena occurring in the object were measured and described, next iteration will answer whether the changes introduced to the product and its operational usage will have a positive effect on the durability parameter.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

M. Drajewicz has conducted the material engineering and lab reports. P. Cichosz conducted research and wrote the paper. S. Rudy: tech supervision. All authors had approved the final version.

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