Towards optimization of stress simulation in real casting-mould systems

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Abstract

The simulation codes using from many years by foundry industry such e.g. Magmasoft, NovaFlow&Solid and ProCast, contain also the thermo-mechanical modules permitting the estimation of mechanical stresses/deformations in casting during its cooling. It is also known that these modules are rarely used because of the very limited thermo-mechanical database especially for ceramic materials such as foundry sand mould. These technologies – castings pouring in non-permanent sand moulds, particularly iron alloys are most often applied in foundry. In our study the method of evaluating the algorithms quality applied in thermo-mechanical phenomena models based on parameters sensitivity testing from the proper database of the simulation system was used [1]. The comparative analyses of both experimental and virtual results were realized (by stress estimation). Methodology of experimental research was resemble to that described in provided that the applied gray cast iron casting of stress bars (grid) were casted in sand mould bonded by organic resins. Also the usefulness of author’s method called Hot Distortion Plus® consisting in acquisition of temperature/distortion curves of heated sample of sand mould material and correlation with curves of their dilatation and also the inverse solution method are signalized as new proposition to estimate the chosen mechanical moulds parameters.

Keywords: Information technology in the foundry industry, Stress modeling, Cast iron castings, Casting-sand mould systems, Foundry simulation codes, Hot distortion plus method

1. Introduction

The thermal theory of foundry processes describes not only the course of heat transfer phenomena in the cast–mould system. The majority of hypotheses of other particular complex phenomena and their combination (coupling) are also related to thermal theory [2].
The successful creation and application of so-called coupled models are more and more frequent. These models connecting energy production and transfer, mass transfer, mechanical phenomena state and their effects are present in the theory and in the practice of foundry. These simulation systems, called also simulation codes are actually widely used in world foundries as the optimization tool for technological studies by Virtual Prototyping method, but they demand permanent improvement studies.
The simplest models often need the parameter identification to be exactly connected with final experiment. When the essential modeling equations are known, we are looking for the missing coefficients in the differential equations. In fact, reconstruction of thermo-mechanical conditions put on mould (heated by the liquid alloy) and study the assumptions to construct suitable apparatus must be based on series of simplifications, together with simultaneous test for standardization and repeatability of the tests [3]. It is also known that these thermo-mechanical modules in foundry simulation codes are rarely used because of the very
limited thermo-mechanical database especially for ceramic materials such as moulding sand [4–6]. These classic technologies – castings pouring in non-permanent sand moulds, particularly iron alloys are most often applied in foundry. In our study the method of evaluating the algorithms quality applied in thermo-mechanical phenomena models based on parameters sensitivity testing from the proper database of the simulation system was used.

2. Problem of data bases - permanent challenge for creators and users of simulation systems

The current opinion of majority users that material data bases in commercial simulation systems are guilty for inaccurate or unsatisfactory prediction results is not quite right. Catalog-encyclopedic bases mentioned above play the role in the system testing data, preliminary data or referenced. This concerns not only physical data attributed to physical law (describing specific phenomenon equation but also data operated the linked coupling empirical models (or criteria) [7].

The consideration mentioned above considers not only typical thermo-physical mould materials parameters (thermal conductivity, specific and latent heat, heat transfer coefficient) but particularly the thermo-mechanical parameters (E – Young’s modulus, ν – Poisson ratio, Re – Yield stress, α – thermal expansion coefficient).

It should be realized that parameters values from data bases received in time-temperature conditions not fitted to conditions of future usage of these parameters. Especially this remark concerns the simplified models which describe the real process. The reason of missing any kinds of possibilities to define the margin of error of quality prediction result basing on virtual modeling seems necessary to analyze and identify.

Set-up example of mechanical parameters for selected materials is shown in Table 1.

Table 1. Comparison of two mechanical parameters (E, α) for chosen materials (approximate from different sources)

<table>
<thead>
<tr>
<th>Material</th>
<th>Young's Modulus (Modulus of Elasticity) E [GPa]</th>
<th>Thermal Expansion Coefficient α [1/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>210-220</td>
<td>about 1.1·10⁻³</td>
</tr>
<tr>
<td>Cast iron</td>
<td>83-170</td>
<td>about 1.0·10⁻³</td>
</tr>
<tr>
<td>Aluminum</td>
<td>69</td>
<td>2.5·10⁻⁵</td>
</tr>
<tr>
<td>Concrete</td>
<td>20-50</td>
<td>1·10⁻⁵</td>
</tr>
<tr>
<td>Wood</td>
<td>9-12</td>
<td>0.5·10⁻⁵</td>
</tr>
<tr>
<td>Quartz (fused)</td>
<td>72</td>
<td>0.6-1.4·10⁻⁶</td>
</tr>
<tr>
<td>Epoxy resins</td>
<td>2.1-5.5</td>
<td>6-21 10⁻⁶</td>
</tr>
<tr>
<td>Mould sans</td>
<td>0.1-100 (???)</td>
<td>1.2.5·10⁻⁵ (???)</td>
</tr>
</tbody>
</table>

3. Stress modules in chosen foundry simulation codes

The most frequent applied simulation systems in foundry technology like Magmasoft, NovaFlow&Solid (NF&S) and ProCast are optionally equipped with Stress modules. It requires the user knowledge already in pre-processing stage. At Fig. 1 such example for NF&S system is presented.

The Stress modules of mentioned simulation codes allows to perform a thermo-mechanical calculation. The typical results which can be obtained are the following: stress distribution, deformations (elastic/plastic), displacements, dynamic gap formation between casting and mould, elastic springback (only for ProCast), die-mould fatigue, hot tears factor [9].

In NF&S there is access to two models Stress: Elastic module and Elasto-plastic model [8].

In Magmasoft system [10] the Stress module enables the solution such problems as Residual stress and distortion, hot tear tendency in sand and die casting (in metallic dies too). These modules are not quite known by users. The specialists in foundries apply it very seldom. There is no literature information about the validation of models applied in mentioned systems and about confirmation of stresses fields prediction.

The indication of potential cracking zones menaced by appearing (in the highest stresses sites) is quite easy to approximate predict for foundryman–specialist even without simulation calculation employment. It always takes place near the hot spots (material agglomeration in the casting walls crossing). The predictions of
these zones using Stress modules of all above listed systems confirm that fact. However the evaluation of casting crack or/and deformation appeared, caused by stress with high probability is impossible. There are need such test investigations as proposed in this paper – e.g. utilization of stress grid (standard in foundry) as validation experiment. There will be comparison of the simulation results with the use of Stress modules for all three simulation systems [11].

There will be the simplest models application in each system (Elastic model). The basic material parameter (Young modulus, Thermal Expansion Coefficient) will be applied in order to estimate models sensitivity comparing with experiment results (standard stress grid made of grey cast iron).

4 Experiments and numerical studies

4.1. Stress grid – experimental research

The test casting as special grid stress (according to proper foundry standard) was chosen to stress level validation. This casting is made of cast iron. The methodology of this test takes into consideration the combined influence estimation on stress level not only specific construction of grid casting but also the type of mould material (mould sand). In Fig. 2 the photo set illustrating the moulding run is presented. The castings were left in mould after pouring for 12 hours. The castings were knocked out and left to cool to ambient temperature. Following after cleaning the middle rod was cut using saw up to spontaneous crack and it was measured the surface of fracture – Sf (Fig. 3).

Fig. 3. Stages of stress grid testing: A – pouring of the moulds, B – individual stress grid casting, C – cutting of middle bar, D – grid after cutting (crack → below saw cut), E – fracture surface (Sf)

From remained bar part it was made tensile bar specimen and determined tensile strength Rm. Knowing the surface of middle bar value (Ø 30mm) – S30 it can be calculated the tensile stress value in analyzed cross section: σbar = Rm (Sf/S30). The σbar value was related to stress level calculating using simulation systems.

4.2. Stress grid – numerical study

In order to perform the simulation tests the NF&S simulation system were used. In all simulation trials the materials were gray cast iron and furan sand. In each system it was used the most simple thermo-mechanical module – i.e. elastic one. The thermo-physical and thermo-mechanical mould materials parameters were shown in Table 2.

Table 2.

<table>
<thead>
<tr>
<th>Material parameter</th>
<th>Mould sand</th>
<th>Die (steel)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density ρ[kg/m³]</td>
<td>1600</td>
<td>7700</td>
</tr>
<tr>
<td>Specific Heat c[J/kgK]</td>
<td>938</td>
<td>450-750</td>
</tr>
<tr>
<td>Thermal Conductivity λ[W/mK]</td>
<td>1.06</td>
<td>20-31</td>
</tr>
<tr>
<td>Young’s Modulus σy or E(T)[GPa]</td>
<td>0.1-100</td>
<td>140-210</td>
</tr>
<tr>
<td>Yield Stress σy or YS(T)[MPa]</td>
<td>1-10</td>
<td>1-1220</td>
</tr>
<tr>
<td>Therm. Expansion Coeff. α* [1/K]</td>
<td>1·10⁴ or α(T,ρ)</td>
<td>α(T,ρ)</td>
</tr>
<tr>
<td>Hardening Coefficient ν</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

*α = Therm. Expansion Coeff. * not exists as direct data in NF&S
The data for grey cast iron used during all simulations are (from NF&S database): ρ(T)=6950–7500, c(T)=550–800, λ(T)=40–50, E(T)=0.5–100, YS(T)=1–132, u(T)=0.25–0.5.

The simulation results (chosen tests) were show in Fig. 4 to 7. The stress values obtained by simulation were compared with experimental results from stress grid made of grey cast iron. The mean tensile stress from experiment (only with sand mould) is equal to approximately +60 to +90 MPa (Φ30 mm rod) and the compressive stress –40 to –45 (estimated, Φ15 mm rods).

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The extreme materials values of thermo-physical and thermo-mechanical parameters (cited partially in the Table 2) from NFS database et from our experience applied allow to conclude that the calculated results (stress/deformation) obtained with use of steel die data were nearest to real stress values from experience cited above (stress grid casted from grey cast iron in to sand mould). But it’s evident that the casted grid permits to determine the tensile stress in the central Φ30 rod due to both phenomena: contraction of metal and expansion of mould material.

The first attempts of NFS stress model validation show that the separate validation of casting and mould thermo-mechanical parameters for Stress module is the true challenge.
Fig. 7. Fictitious (simplified) stress grid casted in steel die: calculated stress (A) and deformation (B) using Stress module (elasto-plastic) of NF&S system (after 4 min of cooling, $T_{\text{final max}} < 100^\circ C$)

The next figure (Fig. 8.) presents the results corresponding to two cases of virtually tested moulds.

Fig. 8. Calculated stresses on the central section of the moulds (fictitious stress grid) using Stress module (elasto-plastic) of NF&S system. A – sand mould, B – steel die.

The first results with stress/deformation predictions from Magmsoft and ProCast systems aren’t also satisfactory comparing with experiment [11]. In this situation, to complete our investigations, the new series of studies were realized, without applying of molten metal as heat sources to test the mould material (i.e. quartz sand bonded by furan resin).

4.3. Hot Distortion Plus® Test – experimental research

The hot distortion apparatus (DMA [12,13], modified according to Z. Ignaszak idea (with supplementary devices, named: – Hot Distortion Plus® [14]) was applied. Necessary modifications of the DMA apparatus were introduced: i.e. additional gas heating, the Raytek pyrometer and the V50 thermovision camera provided with own recording systems enabling analyzing variable temperature field of the specimen. The modified measuring stand is shown in Fig. 9. Gas heating was used. The specimen temperature was recorded by pyrometer at the side opposite to the heated surface. Temperatures of the heated and side surfaces were recorded by means of the thermovision camera. The sample deformation was measured by special sensor located on the free specimen tip. The photos made during the tests are shown also in Fig. 9. The tests were carried out for the new quartz sand bonded by furan resin (approx. 1%) – chemically hardened by PTS catalyst agent.

Fig. 9. Scheme of the HD Plus® system. Scheme of modified measuring stand containing DMA apparatus.

4.4. Hot Distortion Plus® Test – numerical study

All thermo-mechanical problems considered in this work are governed by chosen partial differential equations (PDEs) with appropriate boundary and initial conditions. Numerical results for 3D systems are obtained using standard computational code COMSOL Multiphysics [15,16]. COMSOL Multiphysics is a powerful interactive environment for modelling and solving the majority kinds of scientific and engineering problems based on coupled partial differential equations (PDEs) using the finite element method (FEM) [17].

The authors show how to estimate the mechanical parameters – Young (elastic) modulus and thermal expansion coefficient – for a rectangular prism sample to achieve satisfactory agreement between experimental and computational results. There is a
A number of physical properties that are temperature independent. In this paper Young modulus \( E = E(T) \) and thermal expansion coefficient \( \alpha = \alpha(T) \) are considered as temperature dependent as well. The principle of homogenization used in this model of porous and multiphase material permits to simplify the volumic characterization of its properties. These temperature dependent relations have great influence on material behaviour and deformation during heating.

The problems are solved with COMSOL code using direct SPOOLES or UMFPACK linear system solver. Relative and absolute tolerance used in calculations are 0.01 and 0.001, respectively. Quadratic Lagrange shape function with tetrahedral element is used for solid stress-strain mode and linear Lagrange shape function with tetrahedral element is used for heat transfer mode.

The theoretical bases of model and numerical methodology were presented in [17,18].

The preliminary test were obtained using constant (temperature independent) values of thermal furan sand coefficients (see Fig.10). The results show very good agreement concerning temperature variations. Simultaneously the comparison of experimental and numerical results for distortion of specimen was non-satisfactory when the constant values of \( E \) and \( \alpha \) were assumed (Fig. 11).

Due to this non-conformity the new approach concerning \( E \) and \( \alpha \) was introduced. The intuitive temperature variations of \( E = E(T) \) and \( \alpha = \alpha(T) \) resulting from our experience on thermo-mechanical behaviours in considered material in the contact with high temperature was analyzed. Many numerical tests were done using the wide range of parameter’s values resulting from \( E = E(T) \) and \( \alpha = \alpha(T) \) formulas. A good agreement between real (measured by HD Plus test) and simulated distortion curves was assumed as the goal criterion.

The final formulas – estimation of temperature dependent \( E = E(T) \) and \( \alpha = \alpha(T) \) allow to obtain expected agreement for measured and simulated distortions (see Fig. 11).

5. Summary

The investigations results obtained by experimental way and simulation method can be summarized as follows:

1. The different ways to investigate the stress/deformation phenomena and to validate the stress modules in the most frequently used foundry simulation codes was described.

2. Applying the mentioned modules which simulate the stress phenomena based on the relatively simplest models the unexplained differences in calculated stress values were obtained.
3. The influence of fine/coarse mesh and also time step are observed for all used simulation codes [17].
4. The complex stress (stress grid construction, presence of gating system) disturbing the run of stress calculations have the heterogeneous character for each codes and influence the virtual stress/deformation maps.
5. The creators of simulation codes (including Stress Module) don’t make algorithm structure available to users. Also the user hasn’t got to estimate the quality of models regarding the simplification state which were applied in stress-displacement model comparing with constitutive law.
6. The obtained results of stress predictions there are not satisfactory yet to apply to predict the stress maps in industrial (often complicated) casting. The decision concerning accepted stress limit by virtual way is not sure. Another modules accessible in described codes (e.g. visco-elastico-plastic) are planned to test in the next stages of study.
7. Using HD Plus® test the interesting validation stage (after thermal validation described in [18]) of coupled model describing the thermo-mechanical phenomena in porous thermolabile materials represented by quartz sand bonded by chemically hardened resin (furan resin with PTS acid), was also presented.
8. It turned out that application of the simplest type of mechanical model (e.g. elastic, in this case) and temperature dependent parameters – E(T) and α(T) – allow to obtain also expected agreement of measured and simulated distortions for sand sample exposed to intensive heating.

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References


