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COMPUTER SIMULATION OF SQUEEZE MOULDING AND VALIDATION OF RESULTS USING INDUSTRIAL COMPUTER TOMOGRAPHY (iCT)

SYMULACJA KOMPUTEROWA FORMOWANIA PRASOWANIEM I WALIDACJA WYNIKÓW W OPARCIU O PRZEMYSŁOWĄ TOMOGRAFIĘ KOMPUTEROWĄ (iCT)

Green sand moulding is still the major method of moulding in foundry industry due to its environmental and financial advantages. Sand compaction plays an important role for the quality of the mould and therefore for the quality of the casting. The determination of optimal compaction parameters is often carried out by trial-and-error-method, which is expensive and time consuming. To improve this situation, the process of compaction is modelled in this work by using different mathematical models based on continuous models. The finite element method (FEM) has been used for the calculation. The theoretical results of the compaction simulation have been compared with the density distribution in the mould measured by computer tomography methods (CT). Graphically enhanced pictures provide insight view into the spatial distribution of the density of the moulding material. The simulation results are in good agreement with computer tomography results.

Keywords: moulding, compaction, FEM, simulation, computer tomography

Formowanie na wilgotno nadal pozostaje główną metodą formowania w przemyśle odlewniczym z uwagi na korzyści ekonomiczne i uwarunkowania środowiskowe. Zagęszczanie masy formierskiej odgrywa ważną rolę dla zapewnienia odpowiedniej jakości formy i, tym samym, odpowiedniej jakości odlewu. Optymalne parametry zagęszczania często są określane metodą prób i błędów, co jest zabiegiem kosztownym i czasochłonnym. Dla usprawnienia, proces zagęszczania modelowany jest przy użyciu różnych modeli matematycznych opartych na modelu ciągłym. Obliczenia prowadzono przy użyciu metody elementów skończonych. Teoretyczne wyniki symulacji porównano z rozkładem gęstości w formie, zmierzonym przy użyciu przemysłowej tomografii komputerowej. Graficznie powiększone obrazy pozwalają na dokładniejsze poznanie rozkładu przestrzennego gęstości formowanego materiału. Wyniki symulacji wykazują dużą zbieżność z wynikami uzyskanymi przy zastosowaniu tomografii komputerowej.

1. Introduction

The sand casting is the oldest and valuable method in casting process. Worldwide about 80% of the casting production is in sand moulding on the basis of clay-bonded mould sand [1]. The quality of castings products in the foundry industry strongly depend on the quality of the mould and the mould sand condition, which in turn depends on a number of factors, i. e. the strength, permeability to gas and density [1, 2]. After the compaction of the mould sand the required quality of the casting can be achieved by selecting the optimum parameters for the size of the sand filling frame and the moulding box, the right distance between models and the moulding box wall, as well as distinct changes in compaction pressure and optimal strength moulding sand parameters. The multitude of influencing factors complicates the optimal combination of these parameters. Hence these parameters are determined by the trail-and-error-method and the experience of experts in the practice.

This method is expensive and time-consuming. To reduce these factors the optimization of the system can be achieved by continuous quality measurements or by simulation. The optimization and improvement of the technical process during the moulding requires knowledge of the developing adhesive forces by contacts between moulding sand, molding box wall, and pattern wall as well as developing cohesion force by the binder. These forces affect the flowing of the moulding sand in the moulding box, particularly in the zones close to

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the models and in model bags. Computer simulations of the compaction process during the moulding allow the influence of these forces to be taken into consideration [3, 4].

The goal of this study is a comparison of measured values of the density distribution from experiments with the results from simulations as well as the validation of the theoretical results. To measure the experiment values the mould must not be destroyed by using industrial computer tomography in this work.

2. Theory

Clay-bonded mould sands are not sufficiently described in the foundry literature regarding the stress – stress distribution and density – density distribution. Therefore literature from other fields such as soil mechanics or powder technology has also been used because many materials from these fields belong to the group of cohesive-frictional materials [5, 6]. Granular media (e. g. sand, powder, gravel) consist of macroscopic particles of different size, shape, and surface properties, leading to specific packing behaviour: disordered structures allow compaction only in connection with reorganisation of parts of the system. Due to friction and plastic deformation, energy is dissipated, so that a system of granular particles is not in equilibrium and, consequently, standard methods of statistical physics cannot be applied. As the foundry literature shows, moulding is studied using different numerical techniques [7, 8, 9]. The most common used techniques are based on continuum mechanical approaches [10, 9] or discontinuum mechanical principles [7].

The term ‘material model’ describes a mathematical model which governs the relationships between stress and strain of mould sand. The development of such a model aims to generate a solution which can be applied in practice. To achieve this, the model should accurately describe the most important aspects of the mechanical behaviour of mould sand. In addition, the required moulding sand parameters should ideally be determined physically from conventional laboratory experiments; this also emphasises the demand for a simple ‘material model’ [10]. Elastoplasticity is a widespread concept for modelling of mechanical behaviour of various engineering materials. It is often used for soils and there is a great variety of elastoplastic soil models of various complexities. The basic principle of elastoplasticity is that stress and strain are divided into an elastic part and a plastic part [4, 10]:

$$\varepsilon_{ij} = \varepsilon_{ij}^{elas} + \varepsilon_{ij}^{plas} \tag{1}$$

The well-known Mohr-Coulomb model and Drucker-Prager model can be considered as a first order approximation of the real soil behaviour, i. e. clay-bonded moulding sand. This elastoplastic model requires five basic input parameters: a Young’s modulus E, a Poisson’s ration ν, a cohesion c, a friction angle φ, and a dilatancy angle Ψ. Since geotechnical and other engineers tend to be familiar with these parameters, the emphasis will be on the above-mentioned parameters [12].

While the strength of a material depends on the cohesion, where the internal friction angle is dependent on the stiffness, the dilatancy of sand however depends both on the density and the internal friction angle. In real soil the stiffness is strongly dependent on the stress level, which means that the stiffness increases with depth. This study deals with a variety of moulding materials, i. e. clay-bonded sand (~94% sand, ~6% bentonite, 2–3% water). Since we are trying to determine the stress and density distribution of materials comparable to some soil types, our moulding materials are treated as soil-like materials and consequently the Drucker-Prager and Mohr-Coulomb approach is applied here. These plasticity models can be freely combined where the combination of the plasticity surfaces defines the total plasticity surface. The resulting Cap Drucker-Prager combines features from both the Cam-clay model and the Drucker-Prager model and is suitable for many geotechnical and powder technology applications.

A much more advanced plasticity model, the Hardening Soil model (HS), has also been developed based on the Mohr-Coulomb-Model [12]. In the Mohr-Coulomb model, limiting states of stress are described by means of the friction angle φ, the cohesion c, and the dilatancy angle Ψ. In contrast to the Mohr-Coulomb model, the HS model also accounts for the stress-dependency of the stiffness modulus, which means that all stiffness’ increase with pressure [12]. It is important to note, that the HS model represents an elastoplastic type of a hyperbolic model, formulated in the framework of friction hardening plasticity. Other features important for soil and moulding materials can also be taken into account with the HS model such as initial or maximum void ratios [4], which then provide additional information about the density development of the moulding material. With the models presented above the main stress can be calculated by integrating the most important moulding material parameters. Elastoplastic models enable the study of many different moulding materials and allow the consideration of important properties such as cohesion, which is often influenced by factors, which cannot be measured or calculated directly.

3. Experimental setup

Moulds usually have a complicated geometry, generating different degrees of compaction and hence different density values. To determine the density of such areas, the mould usually has to be destroyed, which influences the values of the measured density. One way to obtain precise data about the density distribution within a mould is using of industrial computer tomography (iCT). The iCT is a radiological method that produces digital cross-sections of selected areas or complete volumetric pictures of objects to illustrate density and density distribution differences in a short time.

For the determination of the relationship between the iCT density and the real mould density several samples made of quartz sand, bentonite, and water with a known density (Height: 25 mm; Diameter: 50 mm) were produced with a 1 MPa press stamp from above (as described above). These samples have small height to minimize external friction and to obtain an even density distribution within the sample. The sample disks were analyzed through iCT to determine the iCT density. The relationship between the iCT density (ρct) and the real mould sand density (ρr) was determined according to equation 2:

$$\rho r = 0.0002\rho ct - 0.1091 \qquad (2)$$

The reproducibility of iCT measurements was tested for five samples with the same average density (1.3 g/cm^3) at different levels within the sample. Results indicate that this method produces a standard deviation smaller than 0.003 making it useful for this investigation.

4. Determination of the density shift and distribution using ICT

A comparison of measured values from experiments with the results from simulations requires knowledge of the density distribution in the intact moulding because destruction of the mould influences the values of the measured density. This can be achieved using iCT to obtain density data of real mould sand that has been compacted.

To compare experimental results and simulation data a moulding box (100 mm × 70mm × 80 mm) was manufactured with a pattern (Fig. 1) to produce moulds. The density distribution changes due to different pattern geometries within the mould, which also results in a shift of the moulding sand. To observe the shift of the moulding sand during the compaction a metallic powder (Co-powder: > 8.0 g/cm^3) was included as layers in the moulding. Due to the density difference between the metallic powder and the moulding sand the shift of the moulding sand in the different zones can be clearly distinguished (Fig. 2). The influences of the outside friction between the moulding box wall and the mould sand can also be observed by the small shift of the layers at the edge of the moulding.

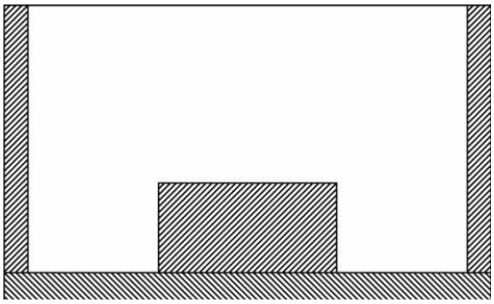

Fig. 1. Mould box with pattern

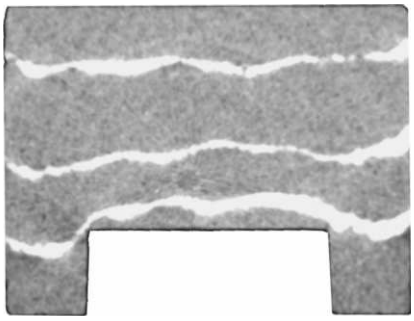

Fig. 2. iCT cross-section of the mould box centre and vertical shift of the metallic powder layer

In the upper section a higher component density of the moulding sand is detected, which indicates a higher density (Fig. 3, Table 1). This occurs because the flowing of the moulding sand is obstructed by the model, leading to an increase in density. Within the lower part of the mould a smaller density is present. Since the moulding box is not symmetrical, flowing of the moulding sand in the wider sections of the moulding box is more prominent than in narrow sections, leading to a different density profile in the lower section of the moulding.

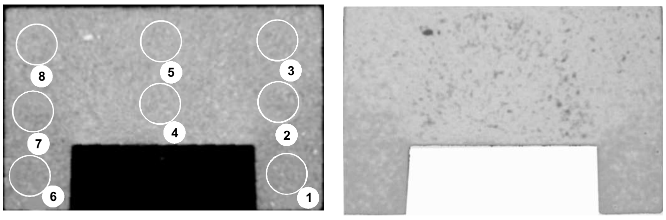

Fig. 3. iCT cross-section (left) and after image processing (right) of the density distribution within moulding

TABLE 1

Density distribution within moulding box

Measuring points	1	2	3	4	5	6	7	8
Real density (g/cm^3)	1.42	1.50	1.55	1.57	1.58	1.40	1.45	1.53

FEM simulations of the density distribution with the model shown above were run to allow comparison of theoretical assumptions of mould density with real measurements (Fig. 4). The boundary condition of simulation for this example are moulding box (100 mm × 70mm × 80 mm), Pressure: 1 MPa from above, Cohesion: 0.070 N/mm^2, Internal friction angle: 22°, Dilatancy angle: 7°.

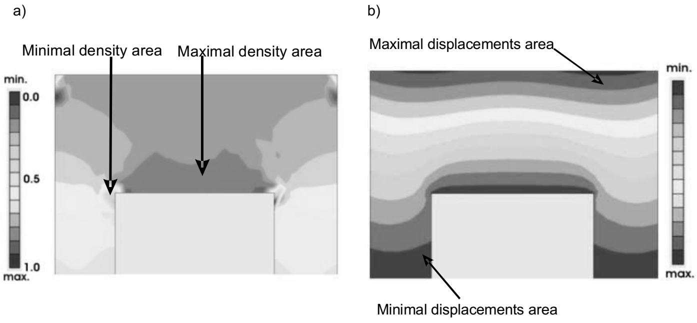

Fig. 4. Simulation of density distribution for mould sand. a) density distribution, b) vertical displacements of moulding particles

The numeric results were validated by comparing with the experimental results (Fig 5). A good agreement can be observed with example.

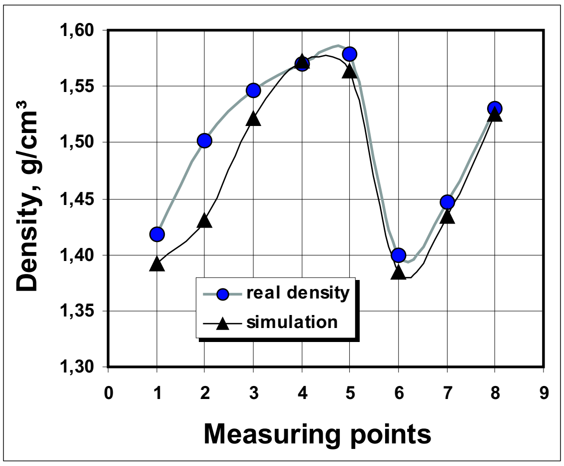

Fig. 5. Comparison of simulation results with experimental values for density distribution

5. Results

The comparison of simulation results with experimental values show good agreement indicating that computer simulations produce a good reflection of reality. Both the density distribution and density shift indicate that in the narrow regions of the moulding box a lower density is present than in the wider regions. In zones above the model the density increases because flow of the mould sand is obstructed. These results are in accordance with the general observations regarding the compaction of mould sand materials [3].

6. Summary

A sand casting model with mould sand including a model was manufactured using compaction as described above. The density distribution within the mould sand was studied using iCT. The relationship between the iCT density and the density of moulding sand was determined with a standard deviation < 0.003. The experimental results were used to simulate the same process using FEM. A comparison of experimental results with numerical data show good agreement of density distribution; differences were due to the model geometry and friction between the mould sand, the model inside and the moulding box wall. The numeric results was validated and then compared with the experimental results.

The comparison of results shows that the iCT method can supply very exact qualitative and quantitative information about the density distribution of the moulding sand. With the help of the developed method new tools are available to predict the density of mould sand without the need for other complex and time-intensive processes.

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