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CHARACTERIZATION OF THE PARAMETERS OF SAND MOULDS IN COMPACTION PROCESS BY USE OF THE INDUSTRIAL COMPUTER TOMOGRAPHY (ICT)

CHARAKTERYSTYKA PARAMETRÓW PIASKOWYCH FORM ODLEWNICZYCH W PROCESIE ZAGĘSZCZANIA Z WYKORZYSTANIEM PRZEMYSŁOWEJ TOMOGRAFII KOMPUTEROWEJ (ICT)

One main problem in moulding is the proper characterization of the local density of the mould, the best without its destroying, for assessment the quality of the mould and to compare results of compaction modeling with experimental results. Industrial computer tomography (ICT) is a technique that allows the non-destructive and contact-free visualization and characterization of the internal and external parts of physical objects including also sand moulds. It is possible to apply ICT technique for the specific research presented here. Moulding sand compaction plays an important role for the quality of the mould and as the consequence for the quality of manufactured casting. The required quality of the castings can be achieved by selecting optimum manufacturing process parameters. The determination of these parameters is often carried out by trial-and-error-method, which is expensive and time consuming. To improve the understanding of the influence of various parameters, mathematical modeling of the compaction processes using numerical solutions was performed. Theoretical results of the compaction simulations have then been compared with practical results of mould compaction obtained by ICT. It was found that simulation results agree well with data from computer tomography and provide insight into the spatial distribution of the density of sand moulds under industrial condition.
Keywords: Industrial computer tomography, sand castings, computer simulation of compaction

Podstawowym problemem w procesie formowania jest prawidłowe określenie rozkładu gęstości w formie, najlepiej metodami nieniszczącymi, w celu oceny jakości formy oraz w celu porównania wyników modelowania procesu zagęszczania z wynikami eksperymentu. Przemysłowa tomografia komputerowa – ICT jest techniką, która umożliwia nieniszczącą oraz bezkontaktową wizualizację oraz charakterystykę wewnętrznych oraz zewnętrznych części obiektów fizycznych, w tym również form odlewniczych. ICT jest możliwe do zastosowania w specyficznych badaniach opisanych poniżej. Zagęszczanie masy formierskiej istotnie wpływa na jakość formy i w konsekwencji na jakość wytwarzanych odlewów. Wymagana jakość odlewów może być osiągnięta przez wybór optymalnych parametrów procesu wytwarzania. Określenie tych parametrów często jest dokonywane metodą prób i błędów, co jest kosztowne i czasochłonne. W celu lepszego zrozumienia wpływu różnorodnych parametrów zastosowano matematyczne modelowanie procesu zagęszczania. Wyniki symulacji porównano z wynikami badań zagęszczenia form z zastosowaniem metody ICT. Wykazano zgodność wyników modelowania oraz wyników pomiarów (ICT), co umożliwia określenie przestrzennego rozkładu gęstości w formie piaskowej w warunkach przemysłowych.

1. Introduction

Computer tomography as a nondestructive testing tool is currently used not only for medical but also for industrial applications to scan small and large objects due to its high resolution capacity. Computer tomography (CT) can be used for the reconstruction and analysis of 2D (layers) and 3D (volumes) objects [1]. CT uses about 50 keV for medical applications and about 440-650 keV for industrial applications. The ability of wall penetration by Macrofocus 450kV extents in plastics materials up to 500 mm, and in aluminum up to 250 mm, and in steel up to 70 mm.

Industrial computer tomography (ICT) can be used to detect differences in density and defects as well as characterize the geometry and position of these differences or defects in the object itself. In addition, concealed inner structures can be detected and measured.

The 3D ICT allows manufacturers to develop new products and methods faster and inspect and optimize the quality of products. The resolution, in the range of μm, is obtained by high-resolution detectors and sources. This type of measuring is very fast compared to other conventional ways [1, 2] especially in the case of the classic mould quality evaluation [3]. The advantage of this method is of course non-contact way of measurement.

Green sand moulding is still the major method of moulding in the foundry industry due to its environmental and financial advantages [2,3,4,5]. Worldwide, about 80% of the

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casting production uses green sand moulding. The quality of castings produced in the foundry industry strongly depends on moulding sand preparing condition [4,5] and the quality of the mould , which in turn depends on a number of factors such as the strength, permeability, surface hardness and density [3,4,6].

The required quality of the mould and as the consequence of the casting can be achieved by selecting the optimum parameters for the size of the sand filling frame and the mould box, the right distance between models and the flask wall, models draft and distinct changes in compaction pressure and optimal moulding sand parameters [4,5,8]. The variety of processing factors complicates the optimal choice of technological parameters. In practice these parameters are often determined by trial-and-error-method based on previous experience.

To improve this expensive and time-consuming method, the optimization of the system can be achieved by continuous quality measurements and computer simulations of the some process. The optimization and improvement of the technical process during the moulding requires knowledge of the developing adhesive forces of contacts between moulding sand grains, moulding box wall, and resulting patterns wall as well as developing cohesion force by

the binder. Computer simulations of the compaction process during the moulding allow the influence of these forces to be taken into consideration [7,8,9].

The goal of this study is to test the applicability of soil mechanical principles and compaction processes to moulding with mould sand materials for the dimensions of a relative large size mould box used in industrial production processes. To enhance our understanding of the relationships between these parameters, mathematical modelling of compaction processes using the Finite Element Method (FEM) is used to generate a computer-aided model to compare theoretical results with practical findings and determine the right combination of parameters.

2. Theory

The development of a material 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 behavior of moulding sand. In addition, the required moulding sand parameters should ideally be determined physically from conventional laboratory experiments; this also emphasizes the demand for a simple "material model" [7].

Elastoplasticity is a widespread concept for the modelling of mechanical behaviour of various engineering materials. It is also often used for soils and there are a great variety of elastoplastic soil models of various complexities. The basic principle of elastoplasticity is that stress and strain rates are divided into an elastic part – ε_{ij}^{elas} and a plastic part – ε_{ij}^{plas} as in Equation (1) [7,9]:

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

Moulding sand shows a distinct non-linear behaviour under stress. This non-linear stress-strain behaviour can be modelled at various levels of sophistication, where the number of model parameters increases with increasing complexity. The well-known Mohr-Coulomb model (M-C model) in Equation (2) and the Drucker-Prager model can be considered as a first order approximation of the real soil behaviour; i.e., clay-bonded moulding sand:

$$c + \sigma_m \cdot tan\varphi - \tau = 0 \tag{2}$$

With shear stress- τ, and mean stress- σ_m. This elastoplastic model requires five basic input parameters: a Young's modulus- E, a Poisson's ratio- ν, a cohesion- c, a friction angle- φ, and a dilatancy angle- ψ.

3. Experiment Setup

Moulds usually have a complicated geometry, generating different degrees of compaction and hence different local density values. To determine the density of such areas, the mould usually has to be destroyed, which influences the values of the measured density [3]. One way to obtain precise data about the density distribution within a mould is the use of ICT. This 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 relatively short time. The ICT density is in Hounsfield Unities (HU).

For the determination of the relationship between the ICT density (HU) 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. The reproducibility of ICT measurements was tested for five samples with the same average density (1.3 g/mm^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 (Fig. 1) [2, 9].

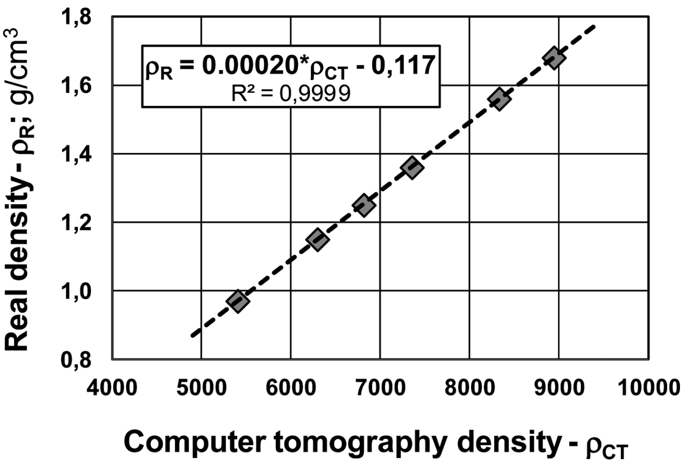

Fig. 1. Relationship between computer tomography density – ρ_{ct} and real density – ρ_{real}

To understand and test the distribution of density in samples made of quartz sand, bentonite, and water with a known density with different height (20, 30, 40, 50, and 60 mm) and diameter: 50 mm. Samples were produced with a press stamp from above. These samples showed a high and mostly uniform density near the stamp (top density) compared to regions away from the stamp towards the bottom of the sample (bottom density). The difference between these locations (top and bottom) increases with increasing sample height because there is friction within the moulding material as well as friction between the material and the wall of the moulding chamber (Figs. 2, 3). This will also apply for more complicated geometries of castings (and of course of the moulds) in the industry. The surfaces with white line are the measured areas of density and for these areas averages density were determined (Fig. 3).

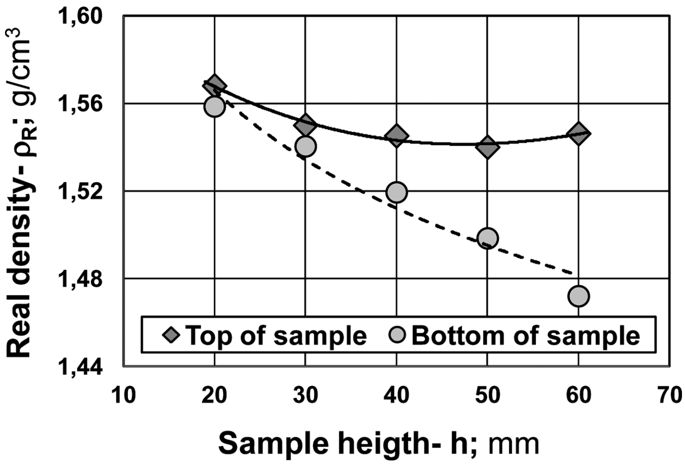

Fig. 2. Relationship between sample height and density

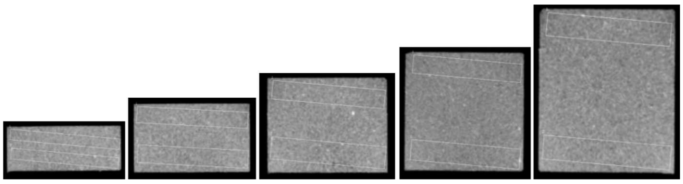

Fig. 3. ICT cross-section of the density distribution within samples with different heights: 20, 30, 40, 50, 60 mm

Comparison of experimentally measured data with the simulation results requires knowledge of the density distribution in the intact moulding since destruction of the mould influences the values of the measured density. This can be achieved using ICT to obtain density data of compacted relatively large size sand mould. To simulate larger-scale industrial conditions, a moulding box (500 mm × 400 mm × 150 mm) with a pattern was constructed to produce moulds. In addition, a multi-compact molding machine – Fig.4a was employed to producing the sand moulds. With this machine different methods of compaction can be investigated (one-plate squeeze moulding, multi-piston squeeze molding, air-stream moulding). On the Fig. 4b one can see also the flask with model.

Because of the ability of ICT to penetrate sand material, this method can be used to investigate rather part of the mould up to 350 mm with good accuracy and acceptable measuring quality. Because the frame of the moulding box is made of steel and the density difference between the steel frame and the mould sand exceeds the capabilities of ICT to produce acceptable quality data, the steel frame and moulding material cannot be measured at the same time. A solution is to extract a portion of the mould from the moulding box without compromising its integrity. The extracted part of the mould was then placed on a wooden frame for transport without altering both its initial form or density distribution (Fig. 5).

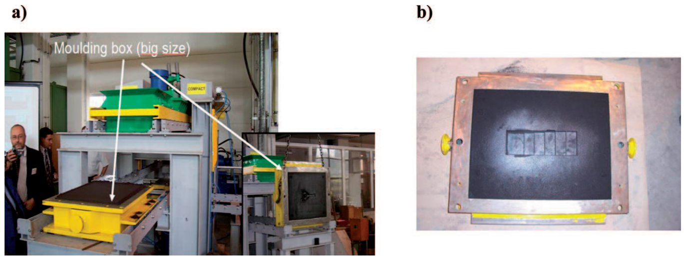

Fig. 4. Multi-compact molding machine – a and moulding flask with pattern (500 mm × 400 mm × 150 mm) – b

Fig. 5. Part of the mould extracted from moulding box

The density distribution within the moulding sand was determined using ICT. The density distribution changes due to different pattern geometries within the mould, which also results in a shift of the moulding sand.

In the upper section a higher component density of the mould sand was detected, which indicates a higher density (Figs. 6 and 7). This occurs because the flow of the mould sand is obstructed by the model, leading to an increase in density. Within the lower part of the mould a lower density was measured. Since the mould box is not symmetrical, flowing of the mould sand in the wider sections of the mould box is more prominent than in narrow sections, leading to a different density profile in the lower section of the mould.

FEM simulations of the density distribution with the Drucker-Prager model described above were conducted to allow comparison of theoretical assumptions of mould density with real measurements (Tab. 1). The boundary conditions used in this example in a mould box are: pressure: 1 MPa from above, cohesion: 0,070 N/mm^2, internal friction angle: 22°, dilatancy angle: 7°.

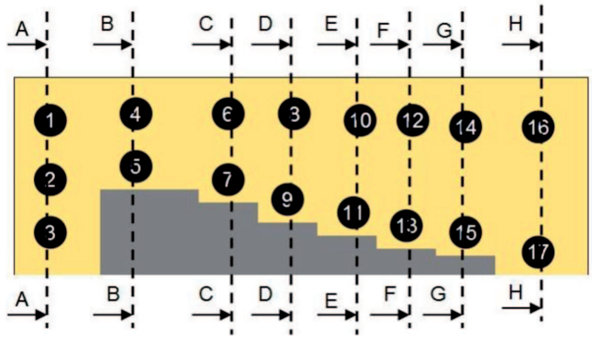

Fig. 6. Mould box with pattern – description of the points of measurements

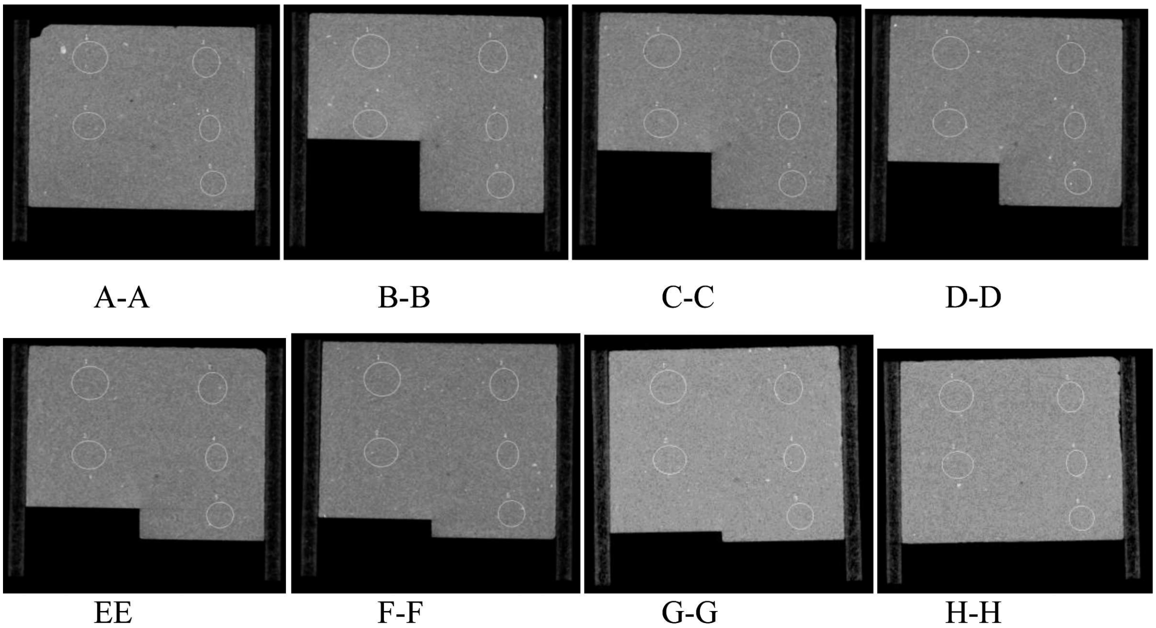

Fig. 7. ICT cross-section of the density distribution within the moulds

TABLE 1

Density distribution within mould and simulation results after validation with experimental values for density distribution (Figs. 6, 7)

Measuring points	CT-Density [-]	Calculated - Density (correlation- Fig.1) [g/cm^3]	Real-Density [g/cm^3]	Numeric Density [g/cm^3]
1	7522	1.39	1.40	1.36
2	7419	1.37	1.37	1.32
3	7392	1.36	1.37	1.32
4	7491	1.38	1.39	1.39
5	7684	1.42	1.43	1.44
6	7466	1.38	1.38	1.37
7	7629	1.41	1.42	1.40
8	7288	1.34	1.35	1.37
9	7204	1.32	1.33	1.37
10	7232	1.33	1.34	1.35
11	7129	1.31	1.32	1.37
12	7035	1.29	1.30	1.36
13	7161	1.32	1.32	1.37
14	7005	1.28	1.29	1.35
15	7198	1.32	1.33	1.36
16	7338	1.35	1.36	1.35
17	7064	1.30	1.30	1.34

4. Results

A good agreement between the simulation results and the experimentally obtained values was observed, which indicates that the computer simulations are capable of producing a realistic approximation of mould production conditions (Tab. 1). Both the density distribution and density shift show that in narrow regions of the mould box a lower density is present than in wider regions. In zones above the pattern (model), the density increases because flow of the mould sand is obstructed. These findings agree with general observations regarding the compaction of mould sand materials [3,6,8].

5. Summary

A moulding box, including a pattern (model), was manufactured using compaction from above by multi-compact machine. The density distribution within the mould sand was studied using ICT.

The relationship between the ICT density and the real density of sand moulds was determined. The experimental results were then compared with the simulation results for the same compaction process using FEM. A comparison of experimental results with numerical data shows good agreement of the density distribution. Differences were due to the pattern geometry and friction between the moulding sand and the pattern inside (or the moulding box wall) and the moulding sand properties determination.

For industrial application the validation of the simulation results shows that the ICT method can produce very precise qualitative and quantitative information about the density distribution in the relatively large parts of the sand moulds. With the help of the method developed here, new tools are available to predict the density of sand moulds without the need for other complex and time-intensive investigation procedures, especially for larger size of moulding boxes.

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