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Cavity prediction in sand mould production applying the DISAMATIC process☆

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ABSTRACT

The sand shot in the DISAMATIC process is simulated by the discrete element method (DEM) taking into account the influence and coupling of the airflow with computational fluid dynamics (CFD). The DEM model is calibrated by a ring shear test, a sand pile experiment and a slump test. Subsequently, the DEM model is used to model the propagation of the green sand inside the mold chamber and the results are compared to experimental video footage. The chamber contains two cavities designed to quantify the deposited mass of green sand. The deposition of green sand in these two cavities is investigated with three cases of different air vent settings which control the ventilation of the chamber. These settings resulted in different air- and particle-velocities as well as different accumulated masses in the cavities, which were successfully simulated by the model.

1. Introduction

The DISAMATIC process [1] is a sand casting process applying green sand as the moulding material [2,3]. The DISAMATIC process is typically used in the automotive industry to produce moulds for metal castings in order to manufacture e.g. brake disks, differential cases and steering knuckles.

The DISAMATIC moulding process has been used since the early 1960s. Compared to conventional green sand moulding processes, it has a vertical parting line. Furthermore, it is a flaskless process, meaning there are no boxes supporting the moulds. The DISAMATIC moulding process is very productive compared to other processes, as it can produce up to 555 moulds per hour. Additionally, it can produce parts with low tolerances. Due to its efficiency and accuracy it is widespread used within the automotive sector.

The ever-rising demands to casting quality, especially within the automotive sector, lead among other things to higher demands to the mould quality. To comply with the higher demands to the mould quality, simulation tools come in handy in the development work having to be done. Until now most of the development work has been based on experience and a trial and error approach as no commercial simulation tools have been available for simulating the combined flow of green sand and air. The lack of commercial available simulation tools is partly driven by lack of material data of the green sand needed to describe the flow. Hence determination of material data has been a major part of this study.

The green sand consists mostly of quartz sand mixed with coal dust, bentonite (active clay) and water, which coats the sand grains to form a cohesive granular material where the green sand flowability is affected by the amount of bentonite and water. In [4] a regression model was applied to determine the relationship between the input value of the sand mixture, i.e active clay, dead clay, water content to the related output values of compactability, compressive strength, spalling strength and permeability. These relationships were developed from a DISAMATIC foundry. The green sand flowability was investigated in [5], [6] and the fluidized viscosity of green sand was investigated in [7]. In [6] it was suggested that the green

☆ Fully documented templates are available in the elsarticle package on CTAN.

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sand can be investigated as a yield stress material and an analytical derivation based on the yield stress material with additional overpressure similar to the conditions when the sand enters the chamber was made in [8]. Tri-axial tests have also been performed on green sand in order to obtain the yield locus in [9]. Uni-axial compression tests were made for green sand and the stress-strain curves were analysed in [10]. Green sand was tested with a ring shear tester obtaining the yield locus and a sand pile experiment in [11].

DEM simulations of the ring shear tester have been performed in [12] where the particle shape, cohesion and static friction were investigated with respect to the resulting tangential pre-shear stress and the peak stress (yield stress). A sensitivity study was performed in [13] simulating a Schulze ring shear tester studying the effect of several material parameters on the resulting tangential pre-shear stress. The resulting tangential pre-shear stress relationship to the particle-particle static friction coefficient ($\mu_{s,p-p}$) was asymptotic up to the value of $\mu_{s,p-p} < 0.70$ and a linear dependence was found on the parameters rolling friction coefficient ($\mu_{r,p-p}$) and the Young's modulus. A DEM adhesive elasto-plastic contact model was used to simulate uni-axial consolidation followed by unconfined compression to failure in [14].

A simulation of the sand casting process with a two phase continuum model has earlier been presented in [15] and continuum models have been designed to model granular materials as e.g. in [16,17]. In [18] a multiphase model was applied to simulate a core shooting process numerically in 2-D and 3-D dimensions. The DISAMATIC process was first studied with a 2-D DEM model in [19] where the granular flow was compared to video footage. This study focused on the deflection of the sand flow causing "shadow effects" around the ribs placed in the geometry of the mould. The model applied a constant particle inlet velocity and particle diameters of 2 mm and 4 mm as representative sand particle clusters for the granular flow. In [11] the same geometry was investigated with a 2-D and 3-D DEM slice model applying the representative particle cluster diameter of 2 mm. A 2-D sensitivity study was performed with respect to the particle-wall interaction which showed the particle-wall values to be of less importance for the flow behaviour and filling times than e.g. particle inlet velocity. The DEM model was calibrated from experiments (ring shear test and sand pile experiment) and afterwards a velocity function for the granular flow was found from video footage.

In this study the framework of [11] is applied for calibrating the DEM model using a ring shear tester to obtain the static friction coefficients and a sand pile experiment for calibrating the rolling resistance and cohesion value for the particle-particle interaction. Additionally the mass of the DEM particle is re-calculated and a slump experiment is used for calibrating the rolling resistance for the particle-wall interaction. Finally a DEM model and a CFD-DEM model are tested by simulating the flow and deposition of green sand in the two cavities and subsequently compared to the experimental observations for the three cases of the air vent settings.

2. Governing equations

2.1. Granular flow: discrete element method

The framework of [11] is applied in this work where the commercially available software of STAR-CCM+ [20] is used for simulating the DISAMATIC process.

2.1.1. Contact notation

The notation for the particle contact is from [21], where particle i and particle j in contact are denoted by their respective positions at $\{\vec{r}_i, \vec{r}_j\}$, the velocities $\{\vec{v}_i, \vec{v}_j\}$, the angular velocities of $\{\vec{\omega}_i, \vec{\omega}_j\}$ and the distance between the two particles are denoted $r_{ij} = ||\vec{r}_i - \vec{r}_j||_2$. The position vector from particle j to i is $\vec{r}_{ij} = \vec{r}_i - \vec{r}_j$ and the normal overlap $\delta_{ij} = (R_i + R_j) - r_{ij} = 2R$ with a uniform radius of R for all the particles.

2.1.2. Normal contact force

The normal force on particle i from particle j can be found as,

$$\vec{F}_{n_{ij}} = \vec{n}_{ij} k_n \delta_{ij}^{\frac{3}{2}} - N_{n_{ij}} \vec{v}_{n_{ij}} + \vec{F}_{coh_{ij}} \tag{1}$$

$\vec{n}_{ij} = \frac{\vec{r}_{ij}}{r_{ij}}$ is the unit normal vector, $\vec{v}_{n_{ij}}$ is the relative normal velocity and δ_{ij} is the normal overlap. $N_{n_{ij}}$ is the normal non-linear damping coefficient, $F_{coh_{ij}}$ is the cohesion, K_n is the stiffness in the normal direction, $N_{n_{ij}}$ is the damping in the normal direction, for further details see [11]. The particle-particle constant cohesion force in the normal direction is,

$$\vec{F}_{coh_{ij}} = -1.5\pi R_{min} W \vec{n}_{ij} \tag{2}$$

$R_{min} = R$ is the minimum radius of contact, W is the cohesion parameter. The cohesion $\vec{F}_{coh_{ij}}$ selected is the Johnson-Kendall-Roberts (JKR) model from [22] with the factor of −1.5.

2.1.3. Tangential contact force

The tangential force on particle i from particle j can be found as,

$$\vec{F}_{t_{ij}} = K_t \frac{\vec{t}_{ij}}{||\vec{t}_{ij}||_2} \delta_{t_{ij}}^{\frac{3}{2}} - N_{t_{ij}} \vec{v}_{t_{ij}} + \vec{T}_{rol_{ij}} \tag{3}$$

$\vec{t}_{ij}$ is the tangential direction of the overlap, $\delta_{t_{ij}}$ is the tangential overlap, K_t is the tangential stiffness, G_{eq} is the equivalent shear modulus, $N_{t_{ij}}$ is the tangential non-linear damping coefficient. The rolling resistance for the particle-particle interaction used is the constant torque method defined as,

$$\vec{T}_{rol_{ij}} = -\frac{\omega_{rel}}{|\omega_{rel}|} \mu_r R_{eq} |\vec{F}_{n_{ij}}| \tag{4}$$

The relative angular velocity between the two particles is defined as $\vec{\omega}_{rel} = \vec{\omega}_i - \vec{\omega}_j$ and the torque from the rolling resistance is $\vec{T}_{rol_{ij}}$.

Note that there is a maximal tangential force due to Coulomb's law,

$$\| \mu_s \vec{F}_{n_{ij}} \|_2 < \| \vec{F}_{t_{ij}} \|_2 \tag{5}$$

the particle-particle static friction coefficient is denoted $\mu_{s,p-p}$ and particle-wall static friction coefficient is denoted $\mu_{s,p-w}$.

2.1.4. Summing the forces

The total resultant force on particle i is then computed by summing the contributions of all particles j with which it currently interacts, thus:

$$\vec{F}_i^{tot} = m_i \vec{g} + \sum_j \left(\vec{F}_{n_{ij}} + \vec{F}_{t_{ij}} \right) \tag{6}$$

where $\vec{g}$ is the acceleration due to gravity. The total torque acting on particle i is given by

$$\vec{T}_i^{tot} = -R_i \sum_j \vec{n}_{ij} \times \vec{F}_{t_{ij}} \tag{7}$$

From these two expressions the acceleration, velocity, position and rotation, are calculated by Newton's second law, numerically for each time step.