NEW DEVELOPMENTS OF FULL-BODY DECORATION TECHNOLOGIES FOR CERAMIC TILES AND SLABS

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1. ABSTRACT

The development of technologies for decoration throughout the thickness of the ceramic tile dates back to the early 1990s. The aim was to implement the aesthetics of technical porcelain stoneware compared to simple solid-coloured or "salt and pepper" products. Specific devices were therefore developed for the creation of multicolour "demixed" effects by means of simultaneous feeding systems of several spray-dried powders in the pressing phase. The usage of mixtures of colours, grains and flakes, distributed randomly, still allowed the characteristic aesthetic effect of natural granites to be simulated. Research continued to create more precise graphic designs with veins typical of marble and geometric patterns, albeit at low resolution. The explosive growth of glazed porcelain stoneware limited further developments of full-body decoration until recent times. In particular until the production of large slabs decorated with digital inkjet printing.

The opportunity to also use ceramic slabs in the countertop segment, as an alternative to marble and granite, has given new impetus to the development of mass decoration, in particular for the creation of through veins. The new technologies proposed are based on a precise deposition of the powders with suitable digital control devices and on the perfect synchronization of the surface graphics created on the glazing line with normal inkjet printers.

The present study shows how the use of avant-garde computational techniques such as the DEM (Discrete Element Method) has allowed simulation and prediction of the motion of the different ceramic powders. This enabled composition of the desired three-dimensional aesthetic pattern in the slab, in accordance with the graphics that are then applied to the surface, using high-resolution inkjet decoration. Thanks to DEM analyses, it is in fact possible to optimize the geometries of the distribution systems to eliminate any artifact and make the final appearance as "natural" as possible and to match that of the original model. The DEM approach presented here uses a simplified particle interaction model to obtain an acceptable compromise between accuracy and product development time. To achieve this objective, an upscaling of the system pursued, thanks to a coarse-graining approach, is essential.

The use of the DEM was accompanied by calibration of the interaction models between the materials involved and by post-processing tools. These tools project the steady-state results forward in order to make it possible to simulate a production process such as that of decoration in mass, even in the concept design phase, with adequate times for product development.

The combination of these technologies enables creation of ceramic slabs with through veins using automated digital production processes, fully integrated into the latest generation of forming and decoration lines.

Slabs with synchronized mass/surface decoration undoubtedly represent the spearhead of ceramic technology, ideal for the design and furnishing sector.

2. INTRODUCTION

Digital transformation is going to play a key role in developing new technologies for the ceramic industry. While the process digital twin aims to provide new ways to manage the industrial ceramic manufacturing process, physical virtualization of the ceramic process is going to help designers by providing efficient and innovative solutions. While physical testing will always be essential in product development, simulation models bring manufacturers closer to their main goal of finding the best solution with fewer iterations.

Ceramic manufacturing process virtualization can provide performance and manufacturability insights earlier in the development process. It can provide results which are hard or even impossible to measure on physical prototypes. It allows virtual testing to be performed under unusual operational conditions and delivers a robust design. All the main steps of the tile manufacturing process can be simulated to achieve these goals. In the current study, we are going to focus on the decoration step and, in particular, on the full-body dry decoration process. Tile and slab dry decoration plays a major role in the ceramic process, even though it does not involve any physical or chemical transformation of the ceramic material. In fact, full-body dry decoration is based on a combination of granular materials handling processes. The physics which rules these processes can be virtually reproduced and the following paragraphs describe the techniques behind this virtualization together with some example applications.

3. DISCRETE ELEMENT METHOD

The Discrete Element Method (DEM) is a numerical simulation technique developed for analysis and modelling of complex, discontinuous systems composed of a large number of bodies. It was first introduced by Cundall and Strack [1] in 1979 during their studies on granular materials. Over the years, the DEM found application in other engineering fields too and nowadays it represents an established numerical technique among academics and industries. The computational time required, especially when dealing with industrial scales, is still one of the major constraints in the dissemination of this technique. The DEM owes its growing success to the progressive increase in the available computational resources of modern processors.

The DEM is based on a pure Lagrangian approach [2], in which the bodies of the system are discontinuously modelled. At the same time, parameters that define the bodies are evolved individually over time. Following the definition given in [3], a DEM code can be defined only if it allows finite displacements, rotations and complete separation between the bodies that compose the system. The separation of all the particles in a DEM simulation entails the need to study and follow each single trajectory and interaction. This means that a big computational capacity is required.

In a DEM algorithm, the particles are numerically represented by a group of moving points. Each particle is associated with a mass and a shape. Despite the existence of different DEM algorithm types, it is possible to individuate the two basic principles that rule it. The first one is Newton's famous second law which governs the motion of bodies under the action of various forces. The second one is the impact between two bodies: the law which describes these actions is crucial for the DEM. Impacts take place several times in the computations, providing the most important information for the problem being solved. Every DEM algorithm follows two main steps in each simulation. The first step is particle generation inside the simulation domain. The second step is a recursive determination of resultant forces from the bodies' interactions and of motion evolution.

According to the approach used by the algorithm, different kinds of DEM are available. In the present work, the so-called "Soft Particle" approach, as introduced by Cundall & Strack, is used. It is by far the most widespread approach, as it allows analysis of systems with a large number of particles without impairing model accuracy.

The key points of this method are the simplicity of the rigid particle formulation, while also considering the stiffness of the materials constituting the particles. Although deformations are not modelled during collision, bodies are allowed to "overlap". Based on the stiffness parameters, the contact model and the extent of this overlap, the resulting forces are computed. The entity of the overlap will be different according to the velocity of the bodies the instant before the collision and the resulting force generated from the specific interaction model. Consequently, the duration of contact between the bodies will be more or less prolonged. The event is not instantaneous and thus the model uses a temporal discretization using fixed time steps. The time step choice is crucial for correctly modelling the physical system. On the one hand, if the time step is excessively small, it can lead to an excessively long simulation. On the other, it is necessary to avoid exceeding a maximum value beyond which contact resolution occurs without any real correspondence.

Using an incorrect time step for temporal discretization can result in a loss of information due to missed interactions between two consecutive time steps. Another issue can arise when overlap between bodies is significant: in this case the contact forces can become unrealistic and too large, leading the simulation to diverge.

The choice of the correct time step is made based on the following two parameters:

Rayleigh time: $t_{Rayleigh} = \frac{\pi R \sqrt{\rho / G}}{0.1631\nu + 0.8766}$

Hertz time: $t_{Hertz} = 2.87 \left[\frac{(m^*)^2}{v_{max} R^* (Y^*)^2} \right]^{1/5}$

where ρ and G represent the density and the shear modulus of the particle, R is the particle radius and ν is the Poisson coefficient, while Y^*, R^* and m^* are defined as follows:

$$\frac{1}{Y^*} = \frac{(1-\nu_1{}^2)}{Y_1} + \frac{(1-\nu_2{}^2)}{Y_2} \quad , \frac{1}{R^*} = \frac{1}{R_1} + \frac{1}{R_2} \, , \quad \frac{1}{m^*} = \frac{1}{m_1} + \frac{1}{m_2}$$

where Y is the Young modulus of the contact particles, R the radius and m the mass of the particles. v_{max} is the maximum velocity of the relative velocity between the particles. The choice of the time step is usually the minimum value between the 20% of the Rayleigh time and the 10% of the Hertz time.

The contact between bodies is modelled imagining them interconnected through a pair of parallel spring-damper systems, oriented respectively in the normal and tangential directions to the contact surfaces. The resulting force originating from the collision of the bodies can be expressed as:

$$\vec{F} = \overrightarrow{F_n} + \overrightarrow{F_t}$$

where $\overrightarrow{F_n}$ and $\overrightarrow{F_t}$ are the forces oriented respectively in normal and tangential directions. These forces can be expressed as a function of sphere overlapping, relative velocity at the collision time and the material characteristics represented by the stiffness of the spring and the damping factor of the damper.

$$F_n = -k_n \delta_n + \gamma_n v_{r,n}$$

$$F_t = -k_t \delta_t + \gamma_t v_{r,t}$$

where δ_n and δ_t are the overlapping respectively in normal and tangential direction, $v_{r,n}$ and $v_{r,t}$ are the components of the relative velocity at contact, con k_n and k_t the stiffness of the elastic springs used to model the contact γ_n and γ_t the damping factors of their respective dampers. The n subscript stands for the normal component direction, while the t subscript stands for the tangent component direction. By assuming for simplicity, that the particles have a spherical geometry and defining with r_a and r_b their radii, r_{ab} the distance between the two centres, t_0 the initial contact time, the overlapping δ_n and δ_t are defined as:

$$\delta_n = (r_a + r_b - r_{ab}) \cdot \overrightarrow{n_{ab}}$$

$$\delta_t = \int_{t_0}^{t} v_{r,t} dt \approx \delta_{t,0} + v_{r,t} \Delta t$$

Depending on the functions used to define the stiffness and damping coefficients, the contact force $\vec{F}$ will assume different characteristics, allowing differentiation between different contact models for different materials to be modelled.

Different open source and commercial DEM codes are available in the market, which are able to reproduce complex granular materials in terms of particle shape and interactions. In the present work a commercial code is used.

Once the material model, the particle shape and the physical duration have been fixed, the larger the number of particles the longer the calculation time will be. Modelling an industrial scale system like the ones in ceramic industry means considering a huge number of particles and often long process times. This leads to an unsuitable computational time for product design timing. Different techniques and multiscale approaches have been studied and developed in order to upscale the granular systems modelling from laboratory to industrial scale (e.g., Eulerian models, discrete di continuum approaches, population-based models, etc.). A widespread method in the DEM community is so-called "coarse graining". Once the "coarse-graining" factor, cg, has been defined, the particle radius is increased by this factor and thus the calculation model dimension is reduced by a factor of cg^3. In addition to that, the timestep can also be increased according to previously suggested rules. As described in [4], growing the particle dimension needs to be considered within the physical models as well. However not all the models can be strictly combined with "coarse graining" and thus the analyst needs to be careful with this.

4. DEM CALIBRATION

DEM parameters need to be calibrated according to the studied granular media and the application which has to be simulated. Thus, the validation step of a DEM model is required to check the sustainability of the model features in reproducing the real system behaviour. There's not a general rule to choose and calibrate the right DEM model and its parameter values. According to the application, one model could fit or not the required needs. If tile cold compression is the simulation aim, then a specific cohesive model must be used, while the same powder in zero stress conditions may not require any cohesive model at all.

The choice and the calibration of the contact model is a key point to end up with simulation results close to real ones. The model features used in this work are summarized below:

- Particle shape and size. The material studied is spray-dried ceramic powder for porcelain tile production obtained through the spray-drying process. It can be said that the spray-dried powder is almost spherical, and thus it is appropriate to approximate the simulated granules as spheres (e.g., Figure 1). This assumption leads to a simpler model and less computational effort. A typical Particle Size Distribution, PSD, of the studied particles is depicted in Figure 1: the experimental sieving results can be modelled as the 2-parameter Weibull mass-based distribution (refer to [5] for math details).

The scale parameter is generally around 350-400 μm and shape parameter around 2.5 - 3. Considering these PSD, the DEM analysis dealing with real process has to choose a lower bound for particle size which is actually greater than the actual smallest particles. This leads to a first approximation which is necessary for dealing with large particle systems.

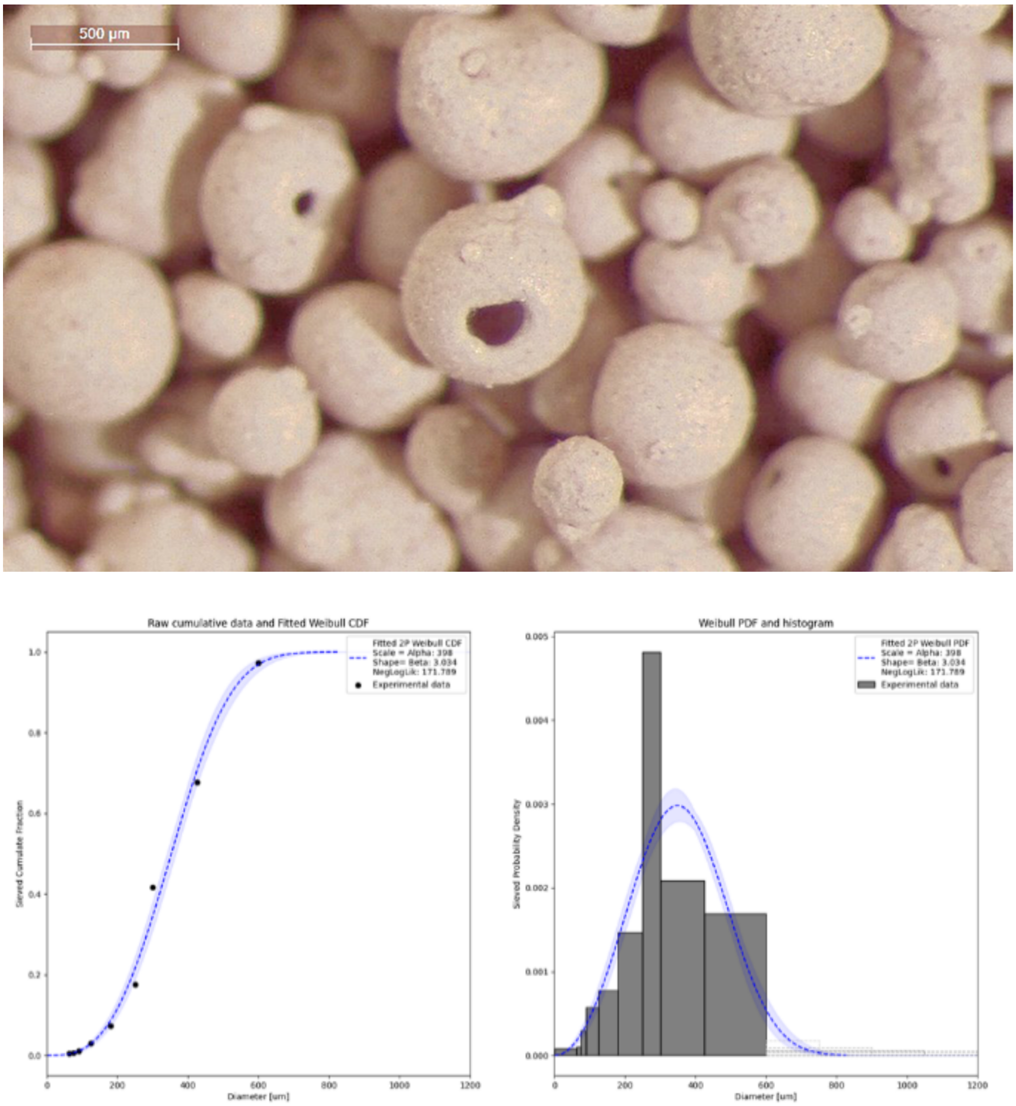

***Figure 1** Microscope picture (left) and typical PSD of spray-dried ceramic powder (right) [6].*

- Particles-particles contact model. Spray-dried ceramic powder can be considered as a free-flowing material according to Jenike's classification [7]. This statement has been shown by Amoros et al [8] and similar results are provided in Figure 2. It shows the shear test results for some spray-dried ceramic powders at different water content (RH). According to this experimental evidence and for sake of simplicity, no cohesion model is used in the present work for those applications which deal with the handling of spray-dried ceramic powder. The contact model chosen for these applications is the so-called non-linear viscoelastic model or Hertz-Mindlin model.

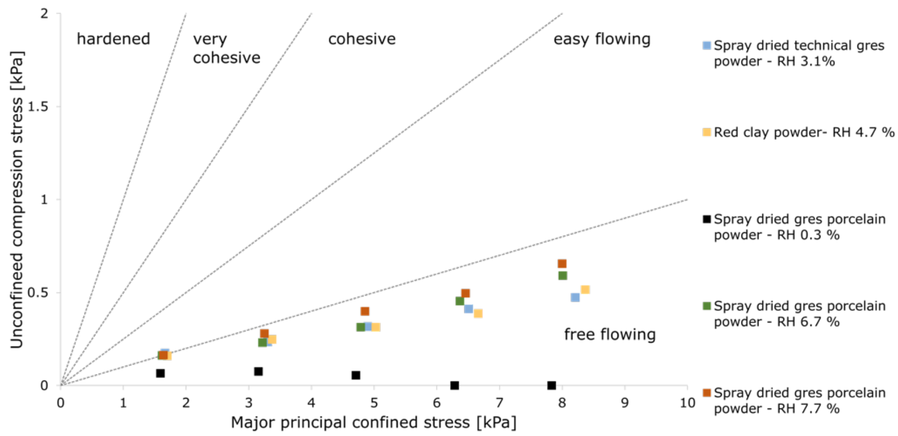

***Figure 2** Shear test results of different spray-dried ceramic powders at different moisture content. Classification according to Jenike's work [7].*

- Particles-wall contact model. The same Hertz-Mindlin model chosen for particles-particles contact is used. If different wall materials are used in the applications, then different contact models could be used. The chosen model is well suited for typical wall materials used in ceramic powder handling applications.
- Rolling friction model. In real physical systems, energy loss due to rolling is related to mechanisms that contribute to hysteresis at the point of contact and the effects of shape. Shape is an expensive thing to model in the DEM: even though the studied particles can be easily considered close to spheres, they're not perfect spheres. A rolling resistance is thus one aspect to consider in the simulation. The model used in this study is a widely used rolling friction model: the elastic-plastic spring-dashpot model with a single parameter [9].
- Coarse graining. The coarse graining coupled with the chosen rolling friction model is not proven to provide coherent results. However, the usage to the combination of these two models provides macroscopic results close to real expectations.

After choosing the simulation models, all the models' parameters must be defined to end with feasible results. Despite the cruciality of choosing the right parameters, there is not one common recognized way to do so. Especially when dealing with cohesive materials there are lot of academic works on models' calibration. In [10] and [11] the authors reviewed DEM calibration procedures while an example of DEM calibration applied to ceramic tile is available in [12]. Here we describe the approach we followed for the current study.

Once the shape and size of the particles have been fixed, the cited used models requires the following parameters to be defined: particles density, ρ_p, particles Young modulus, Y_p, particles Poisson coefficient, Pr_p, particles-particles friction coefficient, cf_{pp}, particles-particles restitution coefficient, cr_{pp}, particles-particles rolling friction coefficient, crf_{pp}, particles-wall friction coefficient, cf_{pw}, particles-wall restitution coefficient, cr_{pw}, particles-wall rolling friction coefficient, crf_{pw}. While Y_p and Pr_p can be chosen directly by the analyst on order to have the right computational timestep without great influence in the considered applications results, all the other parameters are unknown. No direct measurement exists for these parameters: one way to fix their values is to perform some macroscopic tests and reproduce them in the DEM by changing these parameters. In the current context, calibration means solving an optimization problem where the input variables are the cited model parameters while the output variables are the differences between the experimental and simulated outputs. It is well established in the DEM community that more tests are required to completely describe the used models. It's hard to find a single experiment able to provide enough relevant outputs to calibrate all the DEM models parameters. The following experiments have been used to perform calibration for the current study:

Static Angle of Repose: it is a widely used experiment to characterize granular materials [13] and to find DEM parameters. The used setup is a hollow lifting cylinder system and is shown in Figure 3 (left). The assembly consist of a hollow cylinder which is placed on a circular base, filled with powder and then lifted up. The circular base rotates and a camera collect pictures of the heap in order to determine the experiment outputs by automatic image analysis.

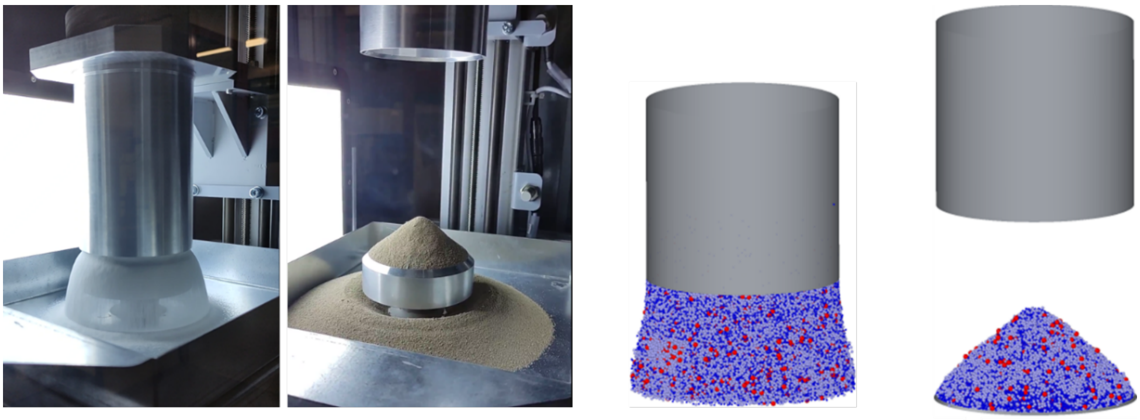

Figure 3 *Static Angle of Repose experimental sequence (left) and DEM results (right)*

Dynamic Angle of Repose: the machine used is a glass drum which can rotate at different velocities as shown in Figure 4. During the rotation, a camera collect pictures and automatic image analysis of the air/material interface provides the experiment outputs.

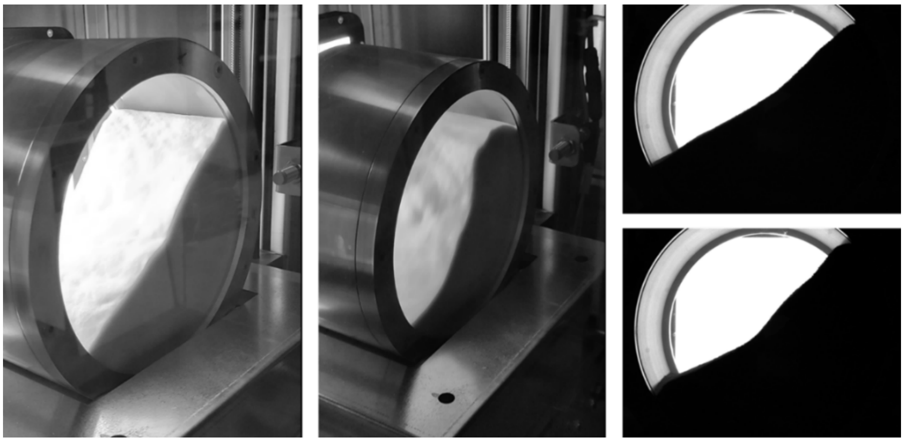

Figure 4 *Dynamic Angle of Repose experimental setup at different velocities*

Tapped Density: it is a standard test to characterize granular materials. Despite the common tapped density instruments, the used setup measures automatically the powder volume. It provides the complete curve of the tapping experiment as shown in Figure 5 (left) and thus different outputs can be obtained (e.g., bulk density, tapped density, Hausner Ratio...).

Discharge Flow: measuring the flow through an orifice is a classical way to define powder flowability. The setup used allows testing of different hole sizes and automatically measuring the mass flow rate in order to obtain output like the one in Figure 5 (right).

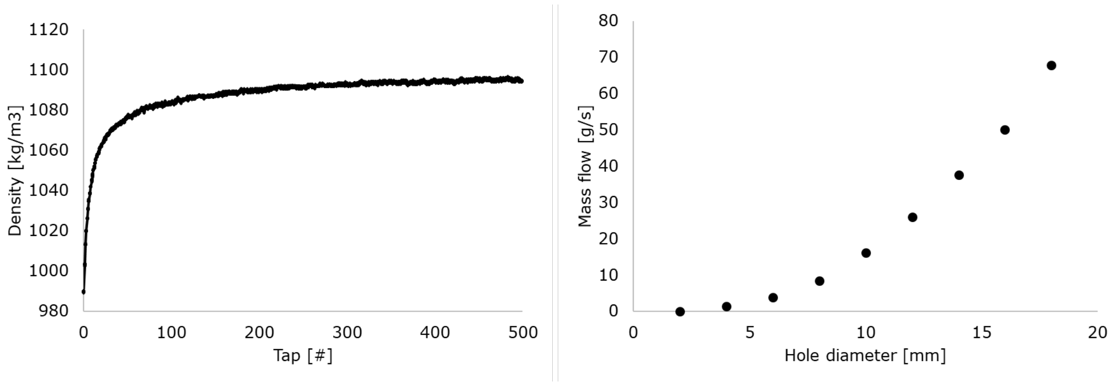

Figure 5 *Tapped density typical output (left) and Discharge Flow typical output (right)*

Inclined wall: measuring the sliding angle of an inclined wall of a certain material is one rude way to estimate the particles-wall interaction. The wall friction test can be used as well to calibrate different particles-wall.

Different calibration strategies can be followed. The most straightforward one is to perform a direct optimization to find the best set of parameters according to the experimental results for a certain powder. A different one is based on the creation of response surfaces for the outputs of the simulations and then on finding the best set by optimizing the inputs according to these surfaces.

The second approach requires more simulations to find the response surfaces, but the optimization is immediate. This second approach can be used for different powders until the PSD used in the simulation is representative of the actual powder PSD. A typical example is considering the same powder with different moisture content. Once the optimal set of DEM model parameters is obtained, it is possible to validate it in the actual applications.

5. APPLICATION EXAMPLES

Full-body decoration involves different handling stages of spray-dried powder: examples of DEM simulations of some relevant applications are provided here.

Digital piezoelectric discharge system

A digital dry decoration discharge system is made up of a hopper and many piezoelectric prongs. Vibration is induced in the prongs to discharge the powder properly in the bottom belt. Prong vibration is activated according to the desired graphical effect. Studying the flow within the hopper of the system is crucial in order to identify the best geometry to reach the desired requirements in terms of productivity and decoration definition. The studied system is depicted in Figure 6 (left): the prong is shown in green, the hopper in black and the mass flow measuring zone in red. The simulation domain is periodic in the Z direction to reduce computational time: only one prong is actually simulated but the results reflect the situation of all prongs working together. The particle colours in Figure 6 (left) represent the particle radius. By changing the geometry of the hopper the discharged mass flow changes. As shown in Figure 6 (right), a good agreement between the experimental and simulated mass flow rate is achieved.

The mass flow rate is one KPI of the current application and, thanks to DEM analysis, different geometries efficiency can be predicted.

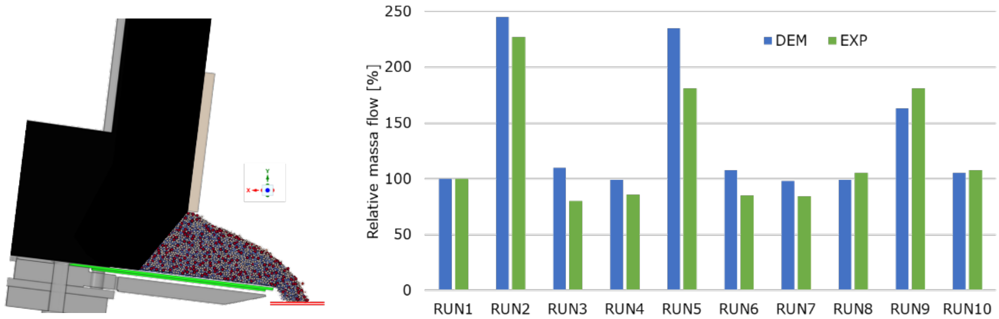

***Figure 6** Simulation results during the discharge phase (left) and comparison of experimental and simulation results in terms of relative mass flow (right).*

Digital full-body powder feeder system

A digital full-body powder feeder system is made up of different hoppers feeding different powders. Each hopper ends in the same common binder thanks to an automatic system of moving actuators which is crucial for the vein definition. One KPI to design this system is the capability of providing a constant certain mass flow despite considering one powder or another. Thanks to the DEM simulation it has been possible to quantify this mass flow and choose the best design according to design requirements. Once a discharge target region is identified, the $target$ variable is defined as follow:

$$target = 1 - \frac{m_{total} - m_{target}}{m_{total}}$$

where m_{total} is the total discharged mass and m_{target} is the mass discharged in the target region. One design objective was to feed the entire mass in the target region, in other words, to have the $target$ close to 1 during the entire discharging phase. In Figure 7 three different simulated actuators results are shown in terms of $target$ during the feeding cycle. The feeding cycle starts at 0 s and ends at 1 s. DEM simulations showed that the actuator corresponding to the green line performs better that the other two.

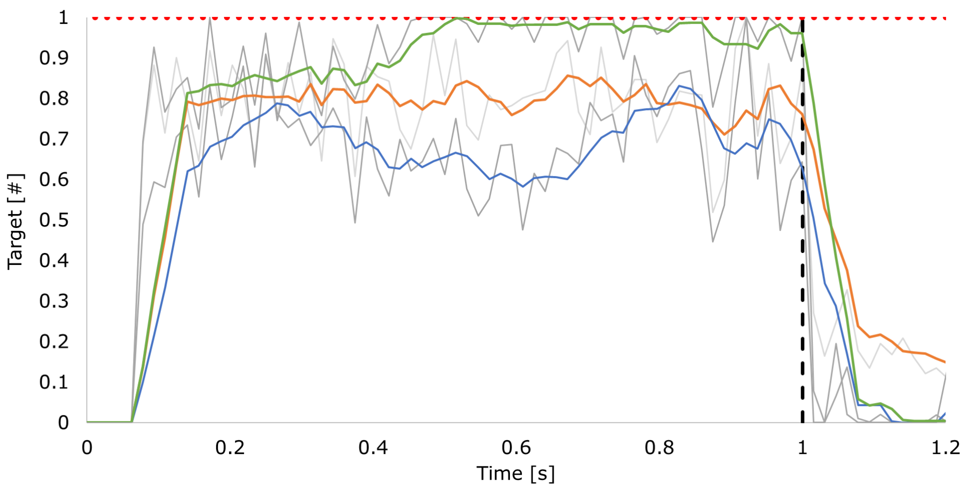

Figure 7 *Target output as a function of time for three different actuators. In grey the point data, in colour the mean averaged values.*

Powder transportation system

Different systems are used to transport the powder bed in the ceramic line. Their design and operation affect vein shape and quality. An example of such a device is shown in Figure 8. The simulation of this kind of apparatus involves around one million particles once the physical domain is limited to a 5 mm periodic domain.

In order to follow vein evolution throughout the entire process, many physical seconds have to be simulated. Such a duration together with the number of particles involved lead to computational times too long to fit with design timing requirements. Thanks to the fact that the particles "flow field" reached a steady state condition after few seconds, only these seconds are simulated with DEM. The vein evolution through the entire process is thus obtained, thanks to a forward projection of the initial vein position according to the stationary granular field [14].

It's a "heuristic" approach which works well under steady state conditions since even if a certain process is long, it doesn't generate new information if it is statistically stationary.

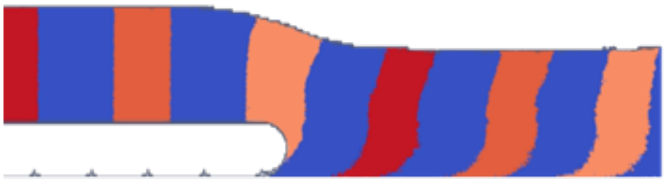

Figure 8 *Example of full-body vein deformation due to transportation.*

6. CONCLUSIONS

The DEM represents a state-of-the-art technique to model granular matters. Its application to industrial scales still faces some issues in terms of computational time and calibration efforts, which is a key point to end with reliable results. Powder handling steps of ceramic manufacturing process can be virtualized by the DEM once the materials involved are well characterized from a DEM point of view. A calibration strategy has been described together with some application examples for full-body decoration. The design of the process for slabs with synchronized mass/surface decoration can exploit the power of physical virtualization to end up with the best possible design.

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