A multibody and discrete element modelling co-simulation approach for robomould process analysis

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ABSTRACT

This paper investigates the impact of robot motion on powder distribution in a novel polymer processing method, known as Robomoulding, which is an advancement of the traditional rotational moulding technique used to produce large, hollow, and stress-free polymer products. To improve this technology, it is essential to understand the effect of process parameters on powder distribution, such as the mould motion and the mould heating rate. When the flow dynamics of the powder is well understood, more advanced motions can be generated that are tailored to a specific product. To achieve this, a combination of a discrete element method (DEM) model and a multi-body dynamic (MBD) model was used to simulate the process. The DEM model was calibrated using a rotating drum experiment that employed a vision-based technique to quantify the powder characteristics. These experimental results were compared to the DEM simulation by measuring the dynamic angle of response. Finally, the section of the product with the most pronounced powder distribution was analyzed by comparing a physical product with the same motion settings. The study concluded that a similar powder distribution trend was observed for a certain setting range when alternating the movement of the process.

Keywords: multibody, discrete element modelling, co-simulation, rotational moulding, rotating drum experiment.

1 INTRODUCTION

Rotational molding is a polymer forming process that is utilized to manufacture large, hollow plastic products. This technique enables the production of seamless parts with a uniform wall thickness. The process involves placing a mould on two perpendicular axes, as illustrated in Figure 1, and rotating it bi-axially. As the mould rotates, heat is applied to it by using an oven, causing the polymer powder to gradually melt and adhere to the inside surface of the mould. It is important to note that not all of the powder melts at once, and the tumbling mass of powder remains mostly in powder form. As the powder tumbles, the parts in contact with the mould or molten powder reach the melting point and melt, sticking to the mould wall to form a thicker wall at that location. Meanwhile, the unmolten powder continues to tumble. After the polymer has been melted, shaped, and cooled inside the mould, the solidified polymer product is removed from the mould. It is worth noting that this polymer forming process is unique because the polymer is processed by melting, shaping, and cooling while still inside the mould [1]. The movement and temperature of the mould during the process cycle play a critical role in determining the quality of the final product. Since gravity is the primary force responsible for spreading the polymer over the mould, the motion of the mould is the primary influence on the distribution of wall thickness. If the wall thickness is uniform, less material is required to achieve the minimum thickness of the part, which has a positive impact on material usage, product weight, energy consumption, and processing times [2]. Different techniques are used to heat the mould, such as forced hot air convection, flame heating, infrared heating, induction, and electrical heating. However, many of these techniques are not energy-efficient when it comes to heating polymer powder inside the mould [1]. During production, these parts are permitted to shrink freely within the mould, thereby preventing any induced stresses, which ultimately results in a highly durable product [2]. The technique is widely used for producing large polymer containers and furniture.

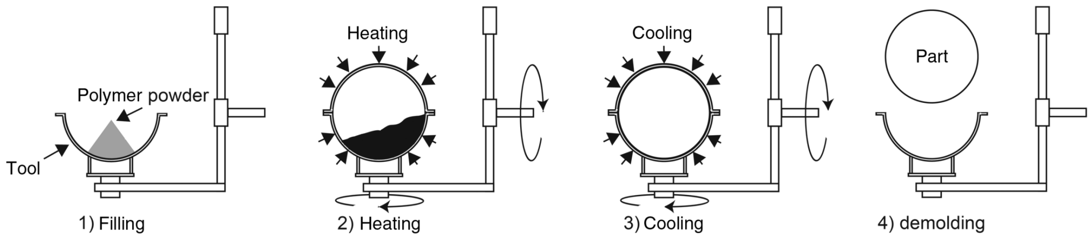


Figure 1. Process steps

1.1 Robomoulding

Robomould, a robotized rotational moulding technique, is a more energy-efficient variation of the traditional rotational molding process. Unlike the bi-axial carousel used in traditional methods, Robomould employs a robotic arm to rotate the mould, allowing for more advanced movements during the process cycle [3]. Additionally, the robot arm can be used to automate the demoulding step before and after the process cycle, allowing for continuous operation of the work cell. Electrical resistors are placed directly on the mould for heating, eliminating the need for an oven and making the process numerous times more energy-efficient than conventional heating methods [1]. These advantages compensate for the long cycle times and increase the output of the process [2].

This setup also provides greater possibilities for motion and heating control, which can possibly result in reduced cycle times. There are numerous parameters, such as the motion of the robot and the heating rate of the mould, that are responsible for the distribution, heating and cooling of the powder. Currently, the trial-and-error method is used to determine the parameters associated with the process, which is time-consuming, resource-intensive, and energy-intensive. The process typically features an air pressure system to aid the melting and solidifying process by ventilating the air within the mould.

1.2 Mould rotation and powder flow

The understanding of the exact effect of many process variables on the resulting quality of the formed product in robomould and rotational moulding, in general, is limited. The rotation speed and speed ratio between the axes used in a rock and roll motion control how and where the powder flows during a process cycle. Varying the rotational speed could improve powder mixing and temperature uniformity within the powder pool, potentially reducing processing time and energy consumption [4]. Research has indicated a linear correlation between powder distribution in a sphere and the contact time between the powder pool and the mould, which is influenced by the size of the powder pool and the ratio of the bi-axial motion. Factors such as the location, direction, and speed of the powder pool passing through a specific spot on the mould determine the amount of powder deposited in that location. Adams et al. [2] supported these findings with a DEM simulation, which showed favorable results [2].

In a slow rotating mould, the motion of powder is primarily governed by gravity. The resulting flow regime depends on several factors, such as rotating speed, friction between particles, and fill level. Extensive research has been conducted to study these flow regimes, and in most rotational moulding processes, a rotating speed between 4-20 rpm is used. The relatively slow angular velocity implies that the powder flow is driven more by gravity than inertia, leading to an avalanching or rolling behaviour [5]. Each flow regime occurs within a specific range of factors like Froude

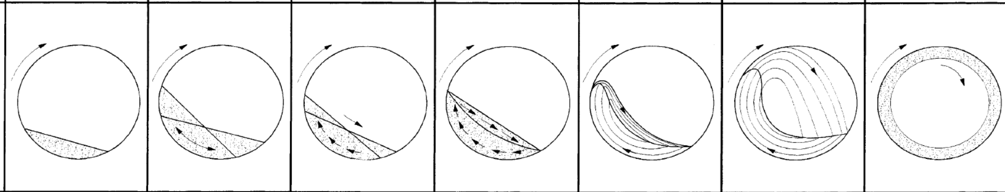
Basic form	Slipping motion		Cascading ("tumbling") motion			Cataracting motion	
Subtype	Sliding	Surging	Slumping	Rolling	Cascading	Cataracting	Centrifuging
Schematic							
Physical process	Slipping		Mixing			Crushing	Centrifuging
Froude number Fr [-]	$0 < Fr < 10^{-4}$		$10^{-5} < Fr < 10^{-3}$	$10^{-4} < Fr < 10^{-2}$	$10^{-3} < Fr < 10^{-1}$	$0.1 < Fr < 1$	$Fr \geq 1$

Figure 2. Forms of transverse motion of solids in rotating cylinders [6]

numbers (Fr), filling degree, particle size, and coefficient of friction, as shown in figure 2. For a uniaxial rotating drum with a horizontal axis of rotation, the Froude number can be determined using $Fr = \frac{\Omega^2 R}{g}$, which relates the acceleration due to gravity (g) to the acceleration due to centrifugal forces ($\Omega^2 R$), where Ω is the angular rotational speed, and R is the radius of the drum [4, 7].

To better explain the factors affecting the flow regime in rotational moulding, it is important to consider the friction between powder particles and between powder particles and the mould. The friction between the powder pool and the mould wall is relatively high, which can lead to a cascading regime. However, reducing the friction between the particles can result in a rolling regime. The friction between particles is also influenced by their shapes, with spherical particles showing a more rolling regime and requiring a higher Froude number and friction coefficient to induce a cascading regime [8, 9]. In practice, mould release agents are often used to easier demould the product but they reduce the friction between the powder and the mould. The cohesion forces in the system also influence the powder flow during this phase, but they are not as widely researched as other factors [4]. Increasing cohesion forces can result in increased friction between the powder and the mould, as well as adhesion between flowing particles. These forces can arise from chemical interlocking between rough surfaces, static effects from particle charging during flow, or the presence of liquids in the system. For instance, unmolten polymer particles can stick to the mould due to tacky liquids or liquid bridges, or due to the sliding of the powder and the process of contact electrification where the particle gets electrostatically charged and sticks to the mould. Overall, these factors play a significant role in determining the flow regime in rotational moulding, and further research is needed to fully understand their impact on the process [4, 5].

1.3 Discrete element modelling

In literature, a discrete element method (DEM) simulation is the preferred method for simulating powder flow [9]. This simulation method describes the elements of the powder, such as size, friction coefficients, and weight, to match the behavior of the physical process. Although the rotational molding process involves three-dimensional particle movements, two-dimensional studies provide a better understanding of flow behavior, and the findings can provide general guidelines for full commercial applications. To this end, a rotating drum experiment using a uniaxial rotating cylinder is commonly used in literature [5]. This experiment examines powder behavior, including flow, fill level, rotation speed, and thermal behavior [4, 5, 8]. It is important to note that the behavior of the powder modeled with spheres differs from that modeled with more irregular shapes [8]. The latter simulation shows a stacking or interlocking mechanism, which leads to a different flow regime.

1.4 Goal and structure of the paper

This paper aims to provide an accurate description of the motion involved in the robomoulding process and combining the MBD simulation with the DEM simulation, while acknowledging the need for certain approximations due to the numerous physical aspects involved. It is worth noting that this study disregards the effects of temperature.

In section 2, we will first discuss the methodology employed, beginning with the calibration of the DEM model to accurately represent the simulated powder. Next, we will discuss the construction of the co-simulation. Following this, we will explain the experimental setup and describe the measurements made. Finally, in section 3, we will delve into the results obtained.

2 METHOD

In this research, our goal is to deepen our understanding of the rotational moulding process through simulation and explore new capabilities related to motion control. However, commercially available simulation software for this process is limited, as noted by Adams et al. [2], who stated that RotoSim is currently the only available package. Therefore, a multibody dynamics (MBD) and DEM co-simulation is developed to simulate the process. All experiments are assumed to be in the same phase of the thermal cycle. During the initial heating of the mould, before the powder starts to melt, the powder has a tendency to slide in the mould and there is no deposition on the mould surface. The second phase, which is the focus of this research, occurs when the mould reaches an elevated temperature that is capable of melting the powder once it comes into contact with the inside wall. This results in a thin, snow-like trace where the powder pool has been. These traces build up every time the powder pool passes until the powder pool is exhausted, and the final layer thickness is established.

The robotic arm that is utilized has six degrees of freedom, which offers more advanced movements than a conventional rotational moulding process. It is not possible to translate or rotate the mould in any direction at any given time because of boundary conditions. However, to generate an appropriate motion for a specific product, a deeper understanding of the interaction of the motion and the flow dynamics is required. Adams et al. [2] proposed a method to create a more uniform wall thickness by rotating the mould in a way that ensures a more uniform wall-powder contact time. For instance, when producing a long and narrow product, the ends of the product usually have a thicker powder wall compared to the long sections in between. Despite its potential advantages, this approach has not been commercially implemented yet. Instead, companies use the classic bi-axial rock and roll motion to produce rotational moulded parts, with some setups allowing certain parameters to be tuned such as rocking angle and speed ratio.

In order to investigate the impact of the rock and roll motion on the process, a DEM simulation is coupled with a MBD simulation. The dynamic simulation is designed to provide a suitable tool for this research and a platform for future iterations. The powder behavior is calibrated using a drum experiment simulated with the DEM simulation, and the parameters are then applied to the DEM-MBD co-simulation. Additionally, the size of the powder pool remains unchanged.

2.1 Powder characterization

To characterize the behavior of the powder used in the study, a series of rotating drum experiments were conducted using the Granutools GranuDrum setup [10], this is a dynamic angle of response

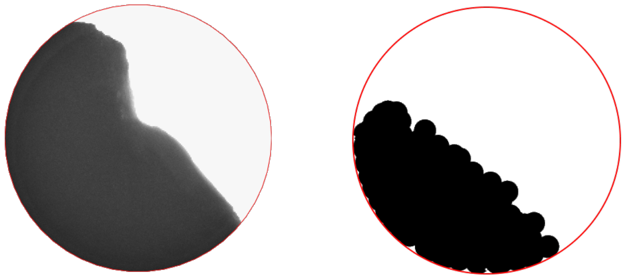


Figure 3. Exported image from the Granutools GranuDrum setup (left) and the DEM-simulation (right)

(DAOR) tester. Since temperature was not considered in the co-simulation, all measurements were performed at room temperature. The data set was obtained by taking 20 images using a built-in vision system at a specific rotational speed of the drum. Ten images were taken while increasing the angular velocity, and ten were taken while decreasing it, to eliminate any hysteresis. The images were captured from the sidewalls of a transparent rotating drum that was backlit. An example of such an image is shown in Figure 3. The software accompanying the Granutools GranuDrum was used to convert the images into scalar values that characterize the powder. The software computes various quantities that describe the characteristics of the powder, with the DAOR being a commonly used parameter to characterize the powder. The DAOR provides the angle between the horizontal and the interface surface between the powder and the air inside the drum [11].

To model the powder in the DEM simulation, the commercial software Mpacts [12] is used and spherical particles are generated that simulate the same total volume as the powder. By using particles with the smallest feasible diameter which still allowed a reasonable calculation time, the overall behavior of the powder is approximated. Each particle has six degrees of freedom, two friction parameters to describe the friction between the particle and the mould (μ_{s-b}) and between the particles themselves (μ_{s-s}), and inertia parameters that can be adjusted by adjusting the specific weight of the material. The utilized parameters can be found in table 1. These parameters can be adjusted to replicate the powder's behavior. To calibrate the DEM model, drum simulations under the same conditions as the physical drum experiments are performed. In a post-processing step, the spheres are projected onto a 2D plane, which is used to take a snapshot of the simulation. The snapshot is then processed using the same algorithm as the Granutools Granudrum, as shown in figure 3. The powder parameters that matched the best behavior of the physical experiments are then used in the co-simulation, where the full-scale robotic arm and mould were modelled.

Table 1. Simulation parameters

Simulation	**Timestep [ms]**	**Sphere radius [cm]**	**Density [kg/m^3]**	μ_{s-s} **[-]**	μ_{s-b} **[-]**
Drum	0.0005	0.3	916	0.1 - 9	0.1 - 9
Co-simulation	0.0005	1	916	9	9

2.2 Co-simulation

The co-simulation that consist of a MBD model and a DEM model, is despicted in Figure 4. The robot arm was modeled with the conventional six degrees of freedom, and a mould was fixed to the last link of the arm, which was modeled as a finite element part. This enabled the motion of the multibody system to be transferred to the DEM simulation and the forces from the DEM simulation to be propagated back to the MBD simulation.

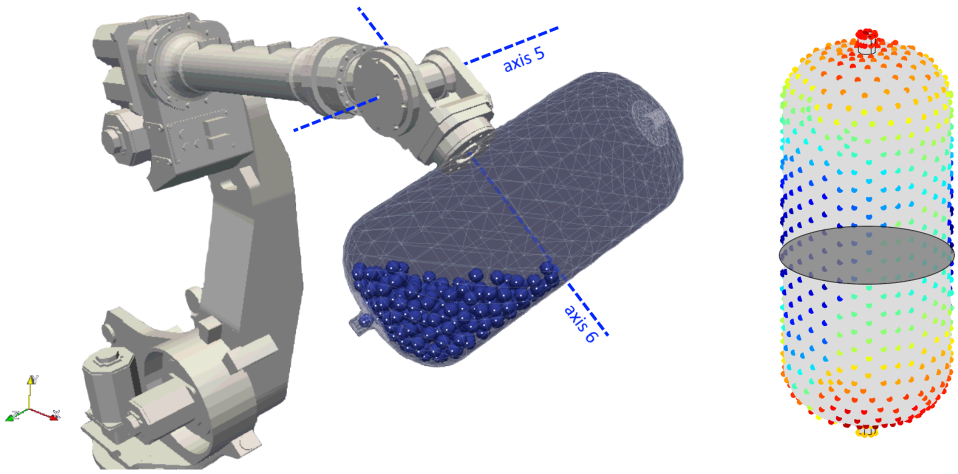


Figure 4. Robomould MBD-DEM co-simulation (left) and the measurement points (right)

The multibody system was modeled using MBRC, an internal multibody tool, and the Flexible Natural Coordinates Formulation (FNCF) method for system dynamics [13]. The rock and roll motion was implemented by moving the two outer axes of the robot, namely axis 5 and axis 6. Axis 5 was used to perform the rocking motion, which was adjusted in this study, while axis 6 was used to perform the rolling motion. During the simulation, the contact forces with the mould were tracked, and the sum of these forces and their locations gave a resulting distribution of the powder by its contact with the mould. To compare the measurements and simulation, the values are normalized with respect to the mean layer thickness since the simulation does not generate an absolute thickness. Parameters used for the co-simulation can be found in table 1. Other quality indicators, such as shrinkage, bubbles, color, and surface roughness, are physical product measurements that cannot be evaluated in the co-simulation.

For this study, a hydrogen tank liner with high dimensional tolerances was selected as the product for simulation and validation. Due to its axial symmetry, the powder distribution around the circumference of the tank could be clearly observed. Here are no edges that disturb the wall thickness. After varying the rocking angle, a qualitative comparison was made between the resulting distributions. To evaluate the quality of the powder distribution, measurement points were chosen on the middle section of the liner, as illustrated in Figure 4. These points formed a circle that intersected the middle of the mould.

2.3 Experimental setup and calibration

The polymer used in the experiments is High Density Polyethylene (HDPE) in powder form, stored at room temperature and humidity. To calibrate the DEM model, the GranuDrum with a cell diameter of 82 mm and a width of 20 mm was utilized, which was filled with approximately 25 grams of polymer powder, resulting in a half-filled drum. The calibration process involved taking 20 images at a certain angular velocity of the drum. This was repeated on another machine to reduce uncertainty.

The physical robomould setup was constructed by combining a FANUC R-2000ia/165F robotic arm with a mould that had a capacity of 82 liters, used for producing the liners of a hydrogen tank. This setup can be seen in figure 5. The existing process enables customization of the rock and roll motion by altering two key parameters: the rocking angle, which corresponds to the motion of axis 5, and the number of rotations of the mould between the outermost positions of axis 5, which corresponds to the ratio between the two rotational axes. The mould is fitted with electrical

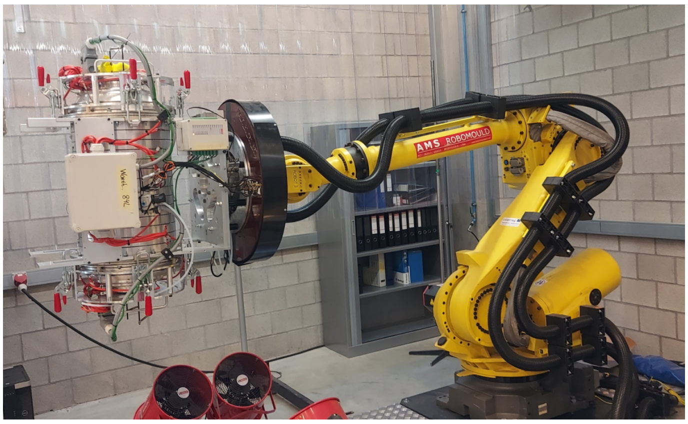


Figure 5. Robomould setup @ KU Leuven, campus Diepenbeek

resistors that provide heating. These resistors are partitioned into zones, allowing for independent control of each zone by adjusting the current flow. Four fans are positioned beneath the mould to facilitate cooling. The cooling rate is adjustable by varying the number of fans utilized. In order to measure the distribution of powder in the product, 240 ultrasonic measurements are taken for each unit. These measurements are then transformed into a heatmap, resulting in an image that visualizes the distribution of powder.

3 RESULTS AND DISCUSSION

This section presents the results of the calibration using the DAOR, followed by a comparison of the measurements with the results of the full process simulation.

3.1 DEM calibration

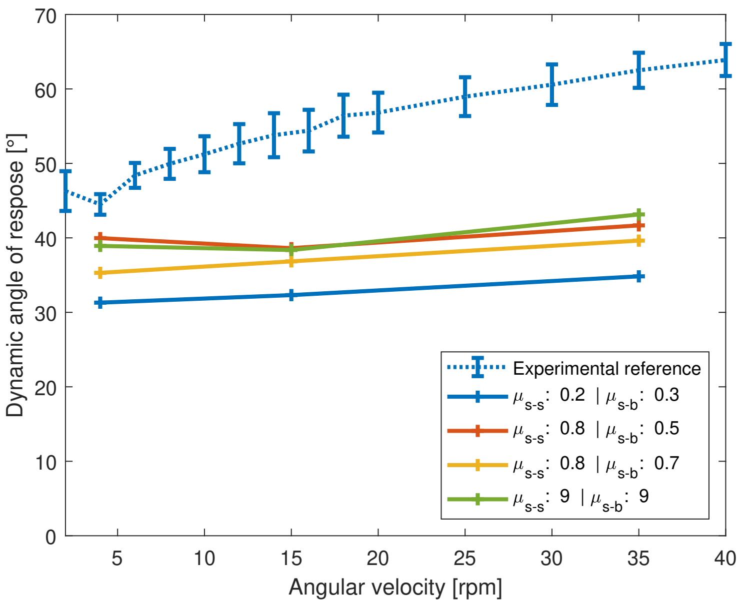


Figure 6. Dynamic angle of response when altering the sphere-sphere friction coefficient

When examining the DEM images of the rotating drum experiment, an active and passive layer is clearly observed, which is consistent with the literature [6, 8]. However, due to the use of back-lighting, the same observation cannot be made with the experimental drum experiments. Nevertheless, it is presumed that a cascading regime of the powder interface is in place, with a similar flowing motion and active and passive layers as observed in the DEM simulation. The active layer of the simulated powder, depicted in figure 3, shows a flatter interface and a rolling motion, as shown in figure 2. The angular velocities of the experiments are arbitrarily chosen at 4, 15, and 35 rpm, resulting in a Froude number of 0.0144, 0.0820, and 1.1016, respectively, with an 82 mm drum. These values are in agreement with the values from figure 2, indicating that the powder should have a cascading motion at 4 and 15 rpm, and a cataracting motion at 35 rpm, which is visually confirmed with the images of the experiment.

When the Froude number is increased in a DEM-simulation under the same conditions, the powder exhibited an increase in DAOR, some configurations of different friction coefficients are shown in figure 6. A similar trend is observed with an increasing friction coefficient. However, the DAOR values obtained from the DEM-simulation are still lower than the reference data set. Further investigation revealed that the shape of the particles played a crucial role in matching the reference data. As noted by Norouzi et al. [8], that different conditions apply on spherical particles to constitute different flowing regimes such as, Froude number, particle size and fill level. The best-fitting values are selected for use in the co-simulation. As confirmed by literature, the best-fitting values came from the highest settings used, being $\mu_{s-s} = 0.8$ and $\mu_{s-b} = 0.3$.

3.2 Process simulation

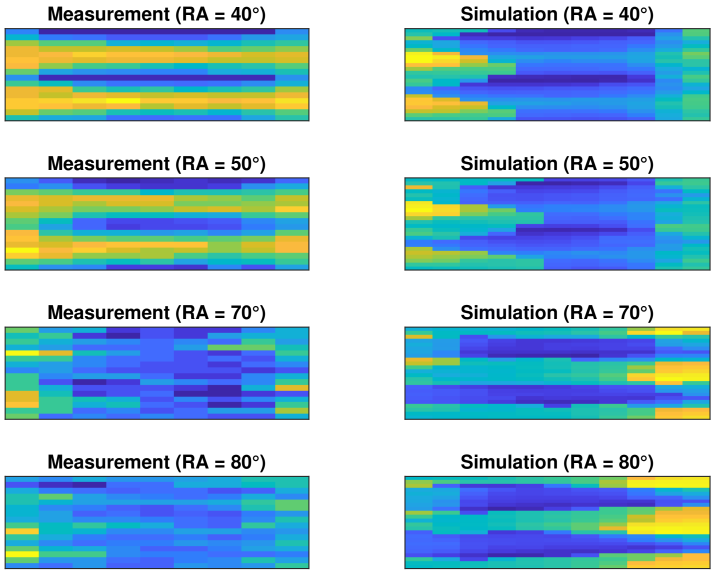


Figure 7. Heatmap of powder distribution at a rocking angle of 40, 50, 70 and 80 degrees

To reduce the simulation time of the co-simulation, only one period of the motion with symmetry and repetition is considered. This approach provides sufficient information to evaluate the quality of the powder distribution. The simulation settings, except for the robot motion, are kept constant, and only the physical reference set's powder distribution is used. The rocking angle's amplitude is altered to change the motion, and four different angles of 40, 50, 70, and 80 degrees are used in the experiments.

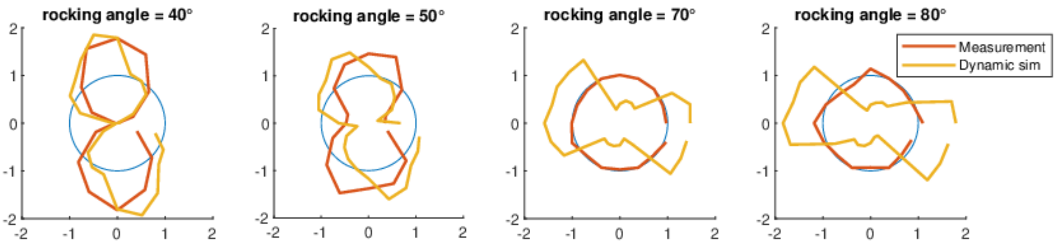


Figure 8. Layer thickness distribution at a rocking angle (RA) of 40, 50, 70 and 80 degrees

The powder distribution on the curved surface of the part was evaluated using a heatmap, as shown in Figure 7. The validation did not consider the powder distribution on the domes' outer parts because they have no distinguishable patterns compared to the curved surface. As noted in section 2, the powder tends to sit longer in these locations due to the continuous rolling motion.

When comparing the powder distribution along the length of the product (dome to dome, horizontal direction in figure 7)), there is less variation between the experimental measurement and simulation results for all the different settings of the rocking angle. However, when examining the distribution along the circumference of the circle (as shown in figure 4), there is a variation in the powder distribution depending on the rocking angle. Figure 8 illustrates these distributions. At a 40-degree rocking angle, the wall thickness distribution of the simulation shows a similar trend to the measurement. However, as the rocking angle increases, the simulation results start to deviate from the measurements. The measurements show a better overall powder distribution at higher rocking angles, whereas the simulation results switch the thick and thin sides at an 80-degree rocking angle. The other simulations (50 and 70 degrees) did not show a clear shifting pattern between the 40 and 80 degree results.

4 CONCLUSIONS

The objective of this study was to investigate the impact of robot motion on the powder distribution of a particular product. The widely used rock and roll motion was chosen for this investigation, as it is commonly used for robomould processes. Understanding the effect of the motion on powder distribution could lead to the development of more advanced motions that can be computed.

To ensure that the DEM elements used to model the powder had the correct properties, a rotating drum experiment was conducted and simulated. Model parameters were adjusted to match the physical powder characteristics, and the behaviour was evaluated using the Dynamic Angle of Response (DAOR). During the calibration of these parameters, two conclusions were drawn. Firstly, the DAOR increased as the Froude number increased, with the powder showing a cataracting motion at higher rotational velocities. However, due to the shape of the spherical particles in the DEM simulation, this behaviour was not observed. Secondly, increasing the friction coefficient between particles and between particles and the mould in the simulation also increased the DAOR, which better resembled the interlocking mechanism of the raw powder form.

A full process simulation was then conducted using a MBD-DEM co-simulation, where the rocking angle was varied. The results showed good agreement between measurement and simulation at lower rocking angles. However, as the rocking angle increased, the simulation results started to deviate, with the thick and thin zones swapping places. The combination of a DEM and a MBD simulation proved to be a sufficient tool for modelling the robomoulding process, but further research is required to better characterise the powder in a DEM simulation. Ongoing research is exploring the use of non-spherical particles. Once the powder is adequately modelled using a

DEM model, more advanced movements can be tested and implemented, for example the replacement of the slow gravity-driven motion with an inertia-driven motion that uses the powder mass to distribute the powder.

ACKNOWLEDGMENTS

This research was partially supported by Flanders Make, the strategic research centre for the manufacturing industry. I would like to extend my gratitude to my Jarne Vanherck for generously providing the experimental data set used in this research and Granutools for given access to their lab equipment.

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