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Motion control for uniaxial rotational molding

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Abstract
Motion control parameters of rotational molding can affect process efficiency and product quality. Different motion control schemes will lead to varied powder flow regimes exhibiting different levels of mixing and temperature uniformity. The change in nature of powder flow during a molding cycle suggests that varying the rotational speed could improve the powder mixing and temperature uniformity, therefore potentially reducing processing time and energy consumption. Experiments completed investigating powder flow under uniaxial rotation show that savings of up to 2.5% of the heating cycle time can be achieved. This validates the hypothesis that altering the rotational speed to maintain the ideal powder flow throughout the heating cycle can be utilized to reduce the time taken for all the polymer powder to adhere to the mold wall. The effect of rotational speed on wall thickness uniformity and impact strength were investigated and discussed. Results show a strong influence of rotational speed (and powder flow) on the wall thickness uniformity of the moldings with wall thickness uniformity deviations of up to 50% found (within the 2–35 RPM speed range tested).

KEYWORDS
manufacturing, mechanical properties, molding, polyolefins, thermoplastics

1 | INTRODUCTION

Rotational molding is a method used to produce hollow, stress-free, plastic articles by melting polymer powder against the hot internal surface of a metallic mold. While the rotational molding industry is rapidly growing and increasingly competing with injection and blow molding processes,[1] there remains limited technical understanding of the effects of many of the process variables (such as rotational speeds, speed ratios, oven temperature cycles, tool geometry, the position of the tool relative to the axes of rotation, and powder characteristics) on process performance and product quality, which threatens to stifle its growth.

In industry, the mold motion is typically controlled by a constant rotational speed and speed ratio rotating the mold about two perpendicular axes (although more axes of rotation are now available through the use of a robotic arm).[2] The mold rotation speed controls how the powder flows (or does not flow) during a cycle. The speed ratio between the primary and perpendicular secondary axes is used to control the powder coverage across the mold wall which contributes largely to the wall thickness uniformity.[3,4] A specific area within motion control that has not been extensively explored is with the relationships among rotational speed, the powder flow motion, and the powder melting process. This article looks to investigate the effect of motion control (and powder flow motion) on part quality and cycle time for uniaxial rotational molding.

2 | LITERATURE REVIEW

4–20 RPM[1] is the typical range of rotational speeds used within rotational molding, with speeds often chosen based on experience and a wasteful trial and error approach. The effect that motion control has on the material distribution on the mold wall occurs largely during the heating cycle, when the powder heats up, becomes tacky and lays up on the wall layer after layer.[3] Once all of the powder has adhered to the wall the molten polymer is often too viscous to flow and affect the wall thickness distribution,[5] however, the presence of bubbles and shrinkage during the fusion and cooling stages respectively can also have an effect.[6]

Rotational speed is usually set so that the powder pool resides at the bottom of the mold relatively confined so that the coverage of powder on the mold wall can be strictly dictated by how the mold rotates through the powder bed. The selected rotational speed is commonly kept constant throughout the complete rotational molding cycle due to control limitations within existing rotational molding machines and a lack of understanding on how best to change the rotational speed during the cycle. However, it is only during the heating stage that the rotational speed selected affects the molded part. During the cooling cycle, mold rotation is important only to prevent the polymer from detaching from the mold wall (sagging) under its own weight.

The rotational speed and speed ratio determine the number of times a specific area on the mold wall passes through the powder bed and the direction in which it enters and exits the powder bed. This is crucial for the mechanical properties of the finished part such as tensile, impact, and flexural strength.[7–9] The powder-mold contact time is critical to allow the most heat energy to transfer to the powder bed through conduction (the dominant means of heat transfer) over a set period.[10] An appropriate speed would allow sufficient time for the heat energy from the mold to transfer to the powder. However, the time that the mold spends out of the powder pool is also critical as this is when the inner mold wall gains more thermal energy (essentially recharging) to pass onto the powder bed during its next contact phase. It can be said that there is a trade-off between the optimum time to keep the mold wall away from the powder to heat up and the optimum time to bring the powder into contact with that area of the mold wall.[5] A number of heat transfer models have been proposed to model the heat transfer from the mold wall to the powder bed. However, these models assume that the powder bed is either static[11–14] or always flowing in a well-mixed state.[15–17]

Obtained through a trial and error approach, common speed ratios[3] are often used for certain mold shapes as a starting point to molders setting up a new mold (e.g., 4:1 for a sphere, 8:1 for a horizontally mounted cylinder). Optimal rotational speeds are also suggested by Roa and Throne[3] based on the mold shape. However, there is contrary evidence within powder flow analysis research (discussed in Section 2.1) that shows a relationship between rotational speed and the size of the mold in finding the optimum powder flow for rotational molding, that is, the rotational speeds given appear to be optimum for the size of molds used for their experimentation but can be expected to alter for different mold sizes.

Liu and Fu[18] experimentally investigated the benefits of molds enhanced with fins using a uniaxial rotational molding machine with a set rotational speed of 12 RPM. Likewise, Xu and Bellehumeur[19] used a uniaxial machine to complete experiments to study crystallization kinetics. Here, a rotational speed of 6 RPM was chosen. It can be said these speeds are chosen as they have been found to be “suitable”; however, there is no evidence to say that they are optimal.

Crawford et al.[5] states that the rotational speed before the point where powder begins to adhere to the mold wall is not critical. It can be argued that there is an importance to the rotational speed at this stage for two key reasons: first, for shorter cycle times it is important to have a uniform heat distribution in the powder before the first layer of polymer adheres to mold wall and acts as an insulator between the mold wall and the remaining powder bed; second, the initial stage of rotational molding is often used to ensure that the powder is well mixed to eliminate a preproduction process, especially if there are coloring pigments or other additives within the powder that could affect the surface finish quality. Furthermore, it is often advantageous for the smaller polymer particles to adhere to the mold wall first. This improves the surface quality of the finished product and reduces the risk of the visibility of trapped air or pinholes on the surface. The rotational speed during the initial heating stage can either encourage or restrict the segregation phenomenon of the fine polymer particles toward the mold wall.[20]

2.1 | Powder flow motion

The polymer powder flow motion inside the mold is dependent on the rotational speeds used. Too fast a rotational speed and the powder flow motion becomes chaotic, which is predicted to lead to a drop in wall thickness uniformity. Too slow a rotational speed and the powder bed will become static and sit stationary on the bottom of the mold, which may lead to longer heating cycles and reduced part quality. The size of the mold and the distance from the axis of rotation to the mold surface will also affect how the powder will flow due to the centrifugal force acting on the powder.[15] A suitable rotational speed will produce a circulating motion of the powder to allow mixing of the powder to occur to achieve a homogeneous powder bed. A well-mixed powder bed leads to a higher uniformity of temperature throughout the bed and this is optimal for achieving the lowest cycle time of the heating stage.

How the powder is flowing and mixing effects how evenly the heat energy is distributed within the powder bed before and after the undesired insulating effect of the molten layer appears.[21] In order to obtain the optimum rotational speed within a rotational molding cycle, an understanding of how the powder is flowing within the rotating mold is required. The study and modeling of powder (and granular matter) have been a difficult area of research due to the complex nature of inherent yield stress and interparticle friction. There are a number of contact and noncontact forces that can exist between particles within a flowing bed of powder such as Van der Waals, capillary (liquid bridge), and electrostatic forces[22–24] which affects the flow of the powder. Dry powder flow can be categorized macroscopically as being in a flow regime[3] with Mellmann[25] giving a more defined description of different flow regimes including: sliding, surging, slumping, rolling, cascading, cateracting, and centrifuging (Figure 1).

2.1.1 | Froude number

Obtaining each regime is found to depend predominantly on rotational speed, filling degree, wall friction coefficient, and drum diameter, with more recent research investigating the effects of other factors such as particle size distribution,[26] particle shape,[27] and electrostatic forces[28] on obtaining different flow regimes. A range of Froude numbers (Fr) is assigned for each flow regime as a guide (providing other variables such as particle size, powder-wall coefficient of friction, and filling degree are kept within a suitable range). The Froude number can be found using Equation (1) for a uniaxial rotating cylinder which shows the relationship between rotational speed (Ω), mold radius (R), and acceleration due to gravity (g) on the flow regime.

$$\mathrm{Fr} = \frac{\Omega^2 R}{g} \tag{1}$$

Powder flow regimes can be correlated between uniaxial and biaxial rotation. Aissa et al.[29] developed Equation (1) to account for the effect of biaxial rotation on powder flow behavior, which relates to the conventional rotational molding motion of the mold. However, the focus of this study is with uniaxial rotation.

2.1.2 | Rolling regime

Within the rolling regime (Figure 1), the powder is expected to have the maximum mixing rate and the best heat transfer within the powder bed, which in turn can improve the quality of the product and also improve the cycle time.[29,30] The Froude number provided in literature to obtain a rolling regime is correct provided a number of boundary conditions are met, a significant condition being the powder fill. Mellmann[25] suggests that the Froude number for obtaining rolling regime holds true for a cylinder vessel with 10%–50% powder fill while more recent research suggests that polyethylene powder (most popular polymer for rotational molding) obtains the rolling regime from the Froude number when the powder fill percentage is within 17%–50%.[31]

The effect of fill percentages of powder below those needed to satisfy the Froude number is specific to rotational molding for two reasons. First, for thin-walled

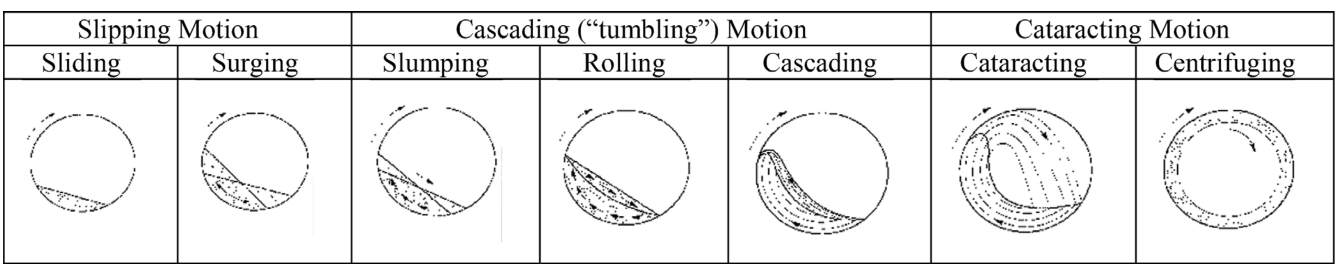


FIGURE 1 Powder flow regimes[25]

molded products, a starting fill percentage of less than 17% is not uncommon and second, as the powder adheres to the mold wall, the powder level will fall below this fill amount. To date, the majority of research investigating flow regime of powder has been from the chemical and pharmaceutical engineering field where the focus is how to achieve the best mixing (homogeneity) of powders to form compounds.[26] In these investigations, having a lower limit to the fill percentage is not a restriction and therefore has not been thoroughly investigated.

Aissa et al.[32] highlights the importance of achieving good mixing of polyethylene powder before melting begins to produce high quality rotationally molded parts and found that the time taken to mix polyethylene powder decreased with increasing particle size and Froude number and decreasing the filling ratio.

Looking further into the rolling regime, it is found that a rolling regime can be obtained at a range of rotational speeds. Nguyen et al.[30] found from a numerical modeling method of powder that it is at the higher rotational speed within the rolling regime that yields the best temperature uniformity. However, the heat transfer investigated was within the powder bed only and neglects the conductive heat transfer efficiency from the mold wall to the powder.

Increased mixing with rotational speed within the rolling regime is in agreement with the findings of Aissa et al.[33] Studies of particle trajectories and velocity profiles of the flow of polyethylene powder during the rolling regime were completed using particle tracking techniques. It was found that the shape of the active layer is an arc from the free surface and that the thickness of the active layer increases with rotational speed. The significance of the active layer thickness is that the active layer is where a majority of the mixing occurs.[34] Therefore, it can be said that the bigger the active layer, the better the mixing conditions. Understanding the factors that affect the active layer thickness allows the mixing conditions within the rolling regime to be optimized. The mixing rate inside the active layer was found to be dependent on fill ratio, Froude number, and particle size.[33]

2.1.3 | Mold release agent

Mellman[25] proposed a critical particle-wall coefficient of friction (below which the powder would cease to flow) that is dependent on the dynamic angle of repose, filling degree, and Froude number. Within rotational molding, mold release agent is often applied to the mold wall at the start of a cycle to facilitate the removal of the molded part at the end of the cycle.[5] However, a potential downside to the use of the mold release agent is that it can act as a lubricant between the mold wall and the powder during the initial heating stage. If the coefficient of friction between the wall and powder falls below the critical coefficient, the use of mold release agent could affect the nature of the powder flow at this stage, which can potentially have an adverse effect on cycle time and part quality. As the effect of mold release agent on the powder flow is relatively unknown, it was decided not to use any mold release agent for the testing.

2.1.4 | Cohesive powder flow

Analysis of dry powder flow relates directly to the initial tumbling stage of the heating cycle (i.e., up to the point when the powder first adheres to the mold wall). Beyond this point, the powder flow will be affected by the increased friction and cohesion from the molten polymer on the mold wall as well as increased adhesion between the flowing particles. Chaudhuri et al.[35] found through discrete element method modeling that increasing the rotational speed for "wet" cohesive powder improved the mixing due to the increased shear in the system, breaking up more coherent particle bonds. This finding correlates to experimental results from Mehrotra and Muzzio[36] who found that the time required to mix cohesive powder reduces with increasing rotational speed (15–30 RPM tested). In a further study by Chaudhuri et al.,[37] it was also found that increasing the rotational speed for "wet" powder has little effect on the heat transfer from the wall mold to the powder bed over the same cycle time.

3 | HYPOTHESIS

Achieving and maintaining a confined, circulating rolling regime during the heating cycle has the potential to accelerate the powder melting process by providing an optimum heat transfer conditions to and within the powder bed, so we propose this hypothesis and conduct tests to prove.

Focusing on obtaining the optimum rotational speed for uniaxial rotation during the rotational molding cycle, the review of the literature within powder flow suggests that there is a relationship between the amount of powder loaded into the mold and finding the most suitable rotational speed to achieve the optimum powder flow regime.

This research will investigate the effect of powder fill on finding the optimum rotational speed. Testing will find the optimum constant rotational speed (Ω) to achieve the shortest heating cycle time with initial powder fill percentages above and below the critical fill percentage (17% fill for polyethylene powder). An increase in rotational speed is expected for powder fill levels below 17%.

As the powder flow motion is expected to change throughout the heating cycle (due to the reducing powder amount, increased particle-particle/particle-wall friction, and presence of cohesive forces) further improvements to the heating cycle time are expected by varying the rotational speed during the heating cycle for a molding cycle with initial powder fill above the critical fill percentage. As the powder adheres to the mold wall and the level of flowing powder drops below the critical level a change in the flow of the powder is expected, and with that, a change in rotational speed is expected to be required to maintain a circulating regime. Increasing the rotational speed as the powder bed level drops and stops circulating is expected to reduce the heating cycle time.

Maintaining a consistent powder position in the mold is predicted to provide improved wall thickness uniformity. The effect of rotational speed (and powder flow) will be investigated to find its effect on wall thickness uniformity.

4 | EXPERIMENTAL SETUP

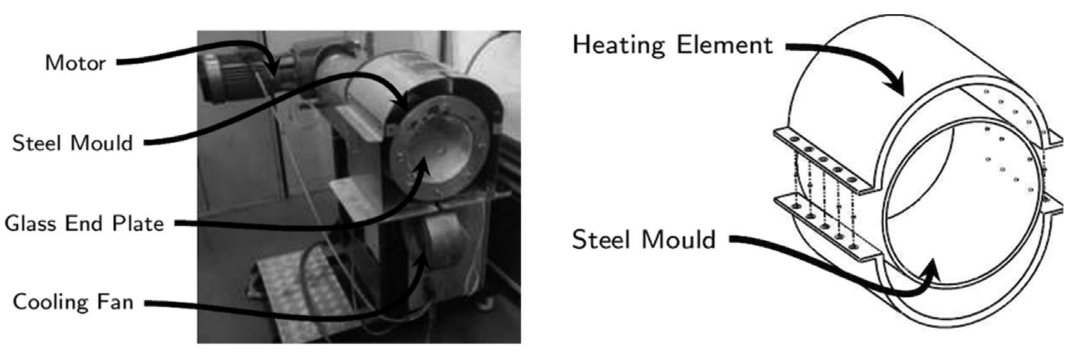
Fifty-four tests were completed investigating the effects of rotational speed during a molding cycle with a cylindrical mold under uniaxial rotation.

4.1 | Machine and equipment

The uniaxial cylinder mold is shown in Figure 2a. The cylinder mold (diameter: 210 mm, length: 220 mm) is rotated by an electric motor and heated by two electrical heating elements (Figure 2b) which wrap around and rotate together with the cylinder mold.

4.2 | Procedure

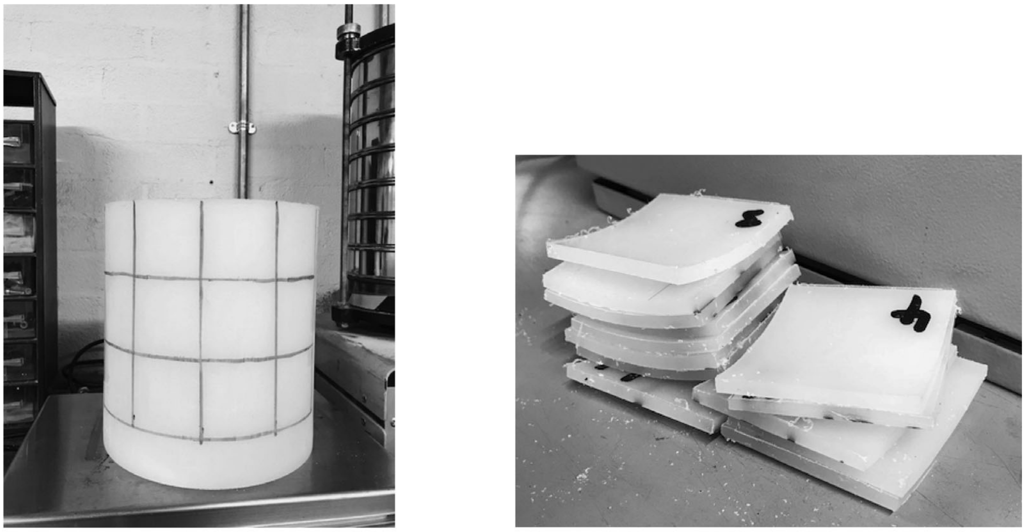
- Mold wall is cleaned of any dirt or plastic residue from previous moldings (no mold release agent was applied to the mold to ensure consistent particle-wall friction).
- Mold is preheated to 30°C.
- Measured amount of medium-density polyethylene (MDPE) powder is loaded inside the mold to achieve a set fill percentage (10% and 30% fills tested).
- End plate is secured and thermocouple inserted through the center of the plate into the center of the mold to allow internal air temperature (IAT) to be monitored and recorded.
- Mold heating and rotation are started simultaneously. Rotational speed is found using a tachometer. The constant rotational speeds tested are 2, 5, 10, 15, 20, 25, 30, and 35 RPM.
- After analyzing the results from constant speed rotation cycles, varied speeds will be tested where the rotational speed is altered during the heating cycle to maintain a flowing, circulating powder bed.
- Heating system is stopped and cooling fan activated when a peak internal air temperature (PIAT) of 200°C is reached and the rotational speed is set to 2 RPM for consistency during the cooling stage.
- Part is demolded when the mold temperature drops to 60°C.
- Each molded part is cut into three sets of 10 test specimens (as shown in Figures 3 and 4) and tested for wall thickness uniformity and impact strength.



(a) Setup of uni-axial moulding machine

(b) Schematic drawing of mould and heating elements

FIGURE 2 Uniaxial rotational molding machine



(a) Cylindrical mould and marked test samples

(b) Cut test samples (60mm x 60mm)

FIGURE 3 Cylindrical mold and test samples

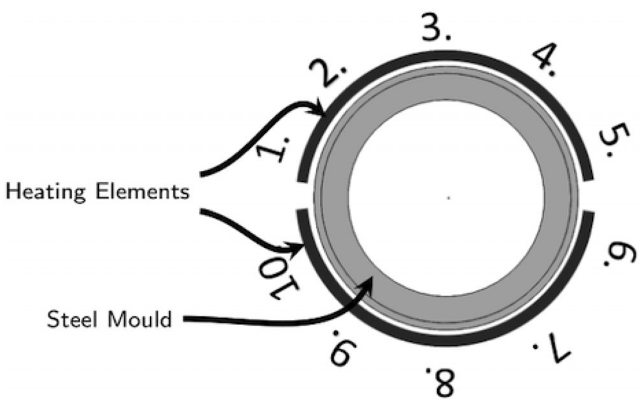


FIGURE 4 Position of test samples relative to the position of the two heating elements

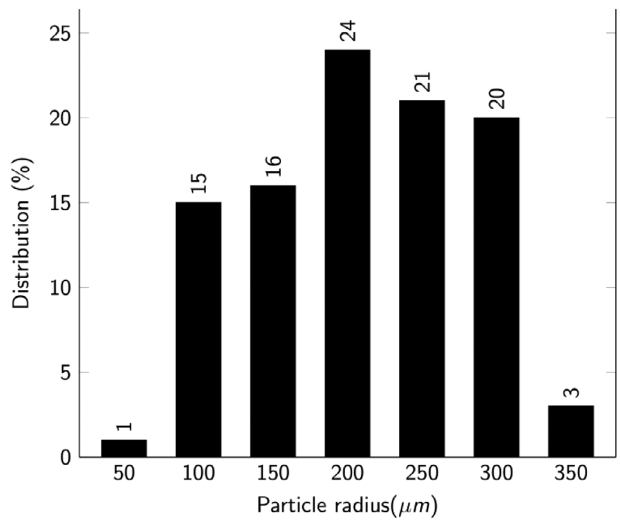


FIGURE 5 Particle size distribution (as per ASTM D1921)

TABLE 1 Powder characteristics

Polymer	MDPE
Density (g/cm^3)	0.935
Bulk density (g/cm^3)	0.353
Melt index (g/10 min)	6
Static angle of repose (degree)	27
Particle size distribution	See Figure 5

Abbreviation: MDPE, medium-density polyethylene.

4.3 | Input parameters

The characteristics of the MDPE powder used for the experiments are shown in Table 1.

5 | RESULTS AND DISCUSSION

5.1 | Induction stage

The effect of rotational speed on the IAT within the uni-axial cylinder during the induction stage of the heating cycle for 30% and 10% powder fills is shown in Figures 6 and 7, respectively. This is the initial stage of the heating cycle where the powder can flow freely against the mold wall until it begins to reach its melting temperature and adhere to the mold wall. The results for 30% powder fill can be correlated to the nature of the powder flow at the

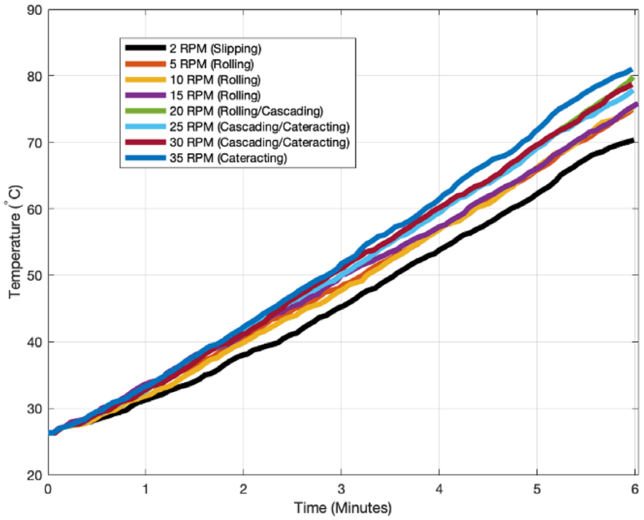


FIGURE 6 Internal air temperature of uniaxial cylinder during induction heating stage of rotational molding cycle—30% powder fill (5 pt. average trendline) [Color figure can be viewed at wileyonlinelibrary.com]

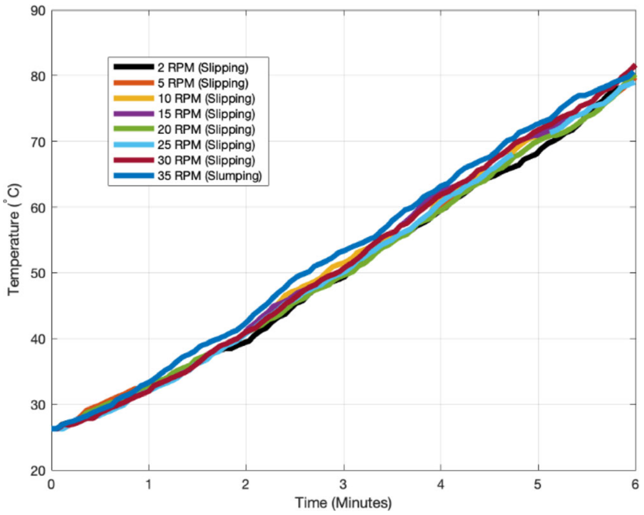


FIGURE 7 Internal air temperature of uniaxial cylinder during induction heating stage of rotational molding cycle—10% powder fill (5 pt. average trendline) [Color figure can be viewed at wileyonlinelibrary.com]

different rotational speeds observed during the test, as shown in Figure 8.

At 2 RPM, a slipping regime is observed where no powder flow or mixing occurs. This rotational speed provided the slowest heat transfer rate to the internal air. This is due to the lack of powder flow causing little heat to transfer from the mold wall through the powder bed and onto the internal air. With an increased rotational speed from 5 to 20 RPM, the rolling/cascading regime can be observed. This circulating flow of the powder was found to increase the rate of heat energy being transferred to the internal air. While the ideal scenario is to efficiently use the heat energy to melt the powder (and less energy is given to the internal air at 2 RPM), the circulating motion allows for the powder to achieve and maintain a uniform temperature which is beneficial during the melting stage of the heating cycle.

Increasing the rotational speed further to 25–35 RPM continues to increase the rate at which the internal air temperature rises. At these speeds, a cateracting regime is observed where powder starts to come away from the mold wall and the main body of powder. This flow motion can be contributed to the increased heat transfer rate to the internal air, with the powder bed holding less of the inputted energy than that with the rolling regime.

For 10% powder fill (Figure 7), little change was observed in IAT for the same range of rotational speeds tested for 30% powder fill. From observations (Figure 9), it can be seen that this is due to the fact that the 10% powder fill level is too low to achieve a circulating regime at the speeds tested. Comparison between 10% and 30% highlights the effect that powder flow has on the heat transfer rates during the induction stage (and not rotational speed). For the same rotational speeds at altered powder fills, different heat transfer rates are observed due to different flow regimes.

Table 2 compares the range in recorded temperatures for 30% and 10% powder fill amounts at three time intervals during the induction stage across all the tested rotational speeds (2–35 RPM). Results highlight the effect of the powder flow motion on the heat transfer mechanism within the system. At 30% powder fill, the powder was observed to flow in many of the flow schemes describe by Mellmann[25] over the speed range and provided a temperature range of 12.2°C at 6 min. On the other hand, the 10% powder fill provided restricted powder flow schemes over the same speed range which was evident in the tighter temperature range of 5.2°C at 6 min.

Figure 10 compares the induction times for a range of rotational speeds at 30% powder fill. This is the recorded time from the start of the heating cycle to the point that powder first adheres to the mold wall. Results show that it is within the rolling/cascading regime that the shortest times are achieved. This is an interesting finding given the fact that for the slipping regime at 2 RPM the powder in contact with the mold wall at the start of the cycle does not flow. This powder is therefore in constant contact with the heat source of the mold wall whereas at higher speeds the powder will circulate so no powder is in constant contact with mold wall. A possible explanation is that the circulating motion has facilitated the filtration of the smaller powder particles, called fines, in the powder

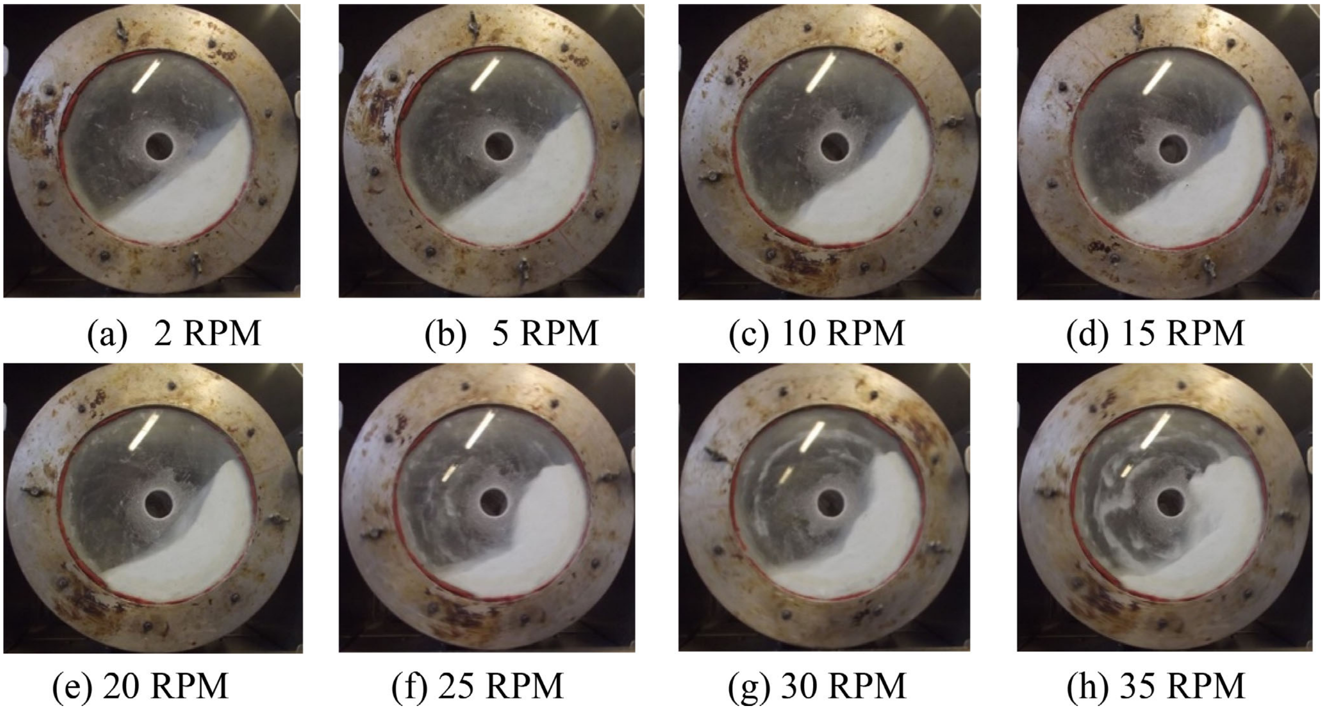


FIGURE 8 Effect of rotational speed on powder flow motion (30% powder fill) [Color figure can be viewed at wileyonlinelibrary.com]

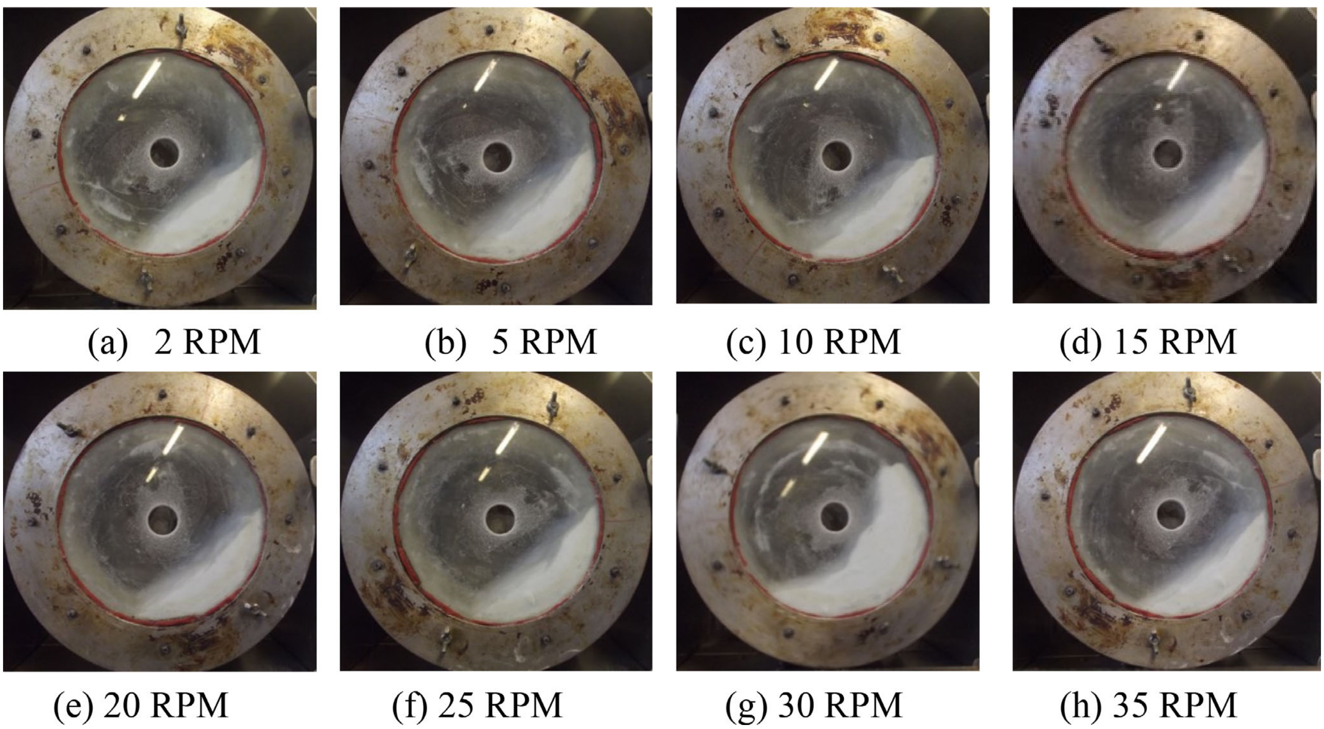


FIGURE 9 Effect of rotational speed on powder flow motion (10% powder fill) [Color figure can be viewed at wileyonlinelibrary.com]

bed to travel around the periphery of the powder bed, that is, closer to the mold wall. The smaller surface area of the fines requires less energy and time to reach its "tacky" temperature and adhere to the mold wall. These findings (shown in Figure 10) found that circulating the powder bed to facilitate the heating and adhering of fines onto the mold wall achieves a shorter induction time of up to 25% when compared to a static powder bed.

As per the findings of Ottino et al.[20] at lower rotational speeds, a segregation phenomena occur where the smaller particles tend to collate in the center of the bed. As rotational speed increases, the opposite is observed where the smaller particles push out to the perimeter of the powder bed. This can be correlated to our results where the time taken for the powder to begin to adhere to the mold wall reduces from 2 to 20 RPM as the percentage of powder fines around the outer regions of the powder bed increases. Beyond 20 RPM, the time taken for the powder to begin adhering to the mold wall increases. While the smaller particles are still flowing around the outer regions of the powder bed, the powder is expected to have a lower bulk temperature due to the cateracting flow regime at these higher speeds and also the reduced contact time interval that the powder layer has with the mold wall for heat transfer.

TABLE 2 Temperature range during induction heating

	Range (°C)		
Powder fill	**2 min**	**4 min**	**6 min**
30%	6.0	8.1	12.2
10%	4.1	4.3	5.2

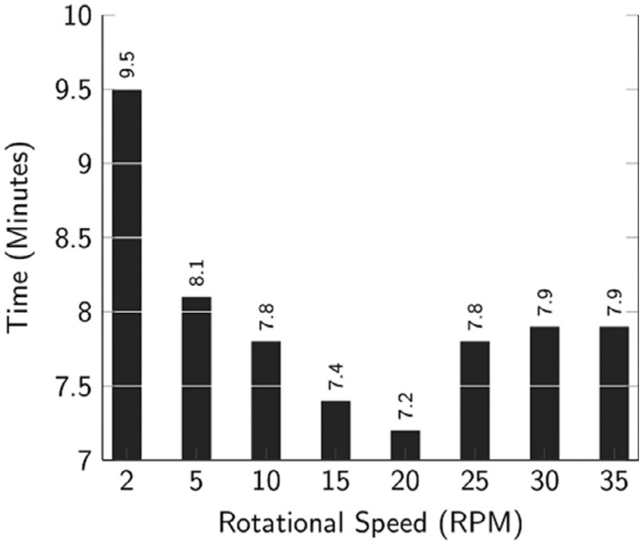
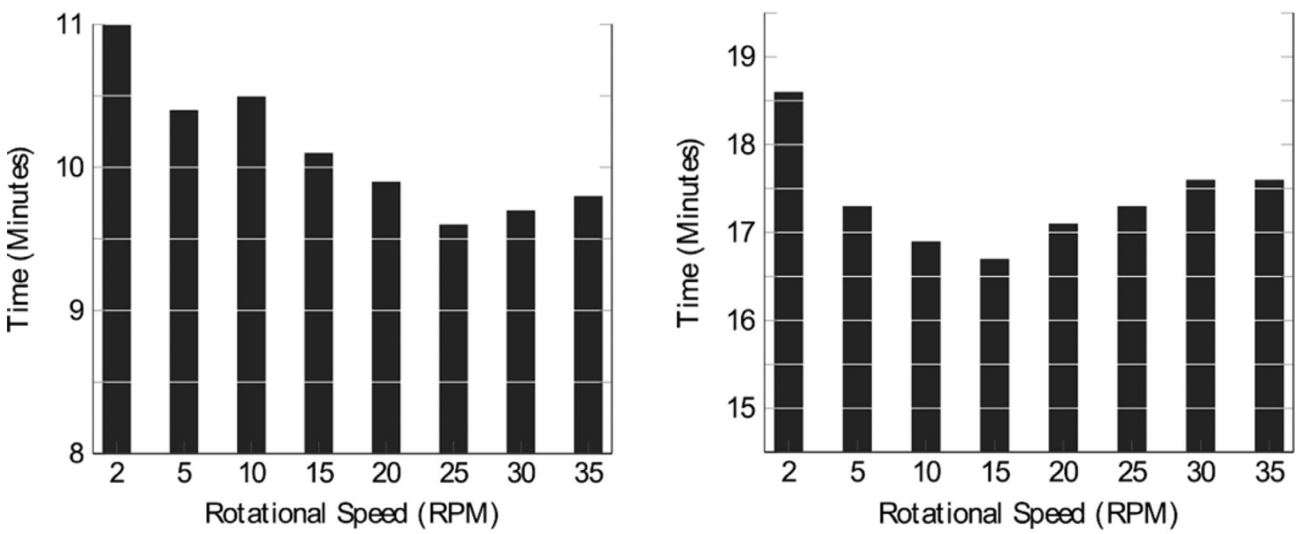


FIGURE 10 Effect of rotational speed on induction time (30% powder time)

In terms of optimizing the overall heating cycle time, having the shortest induction time does not necessarily guarantee the shortest heating cycle time. There are several other factors that can have an influence during the melting stage. Different powder flow patterns are observed once the melting stage has begun and as the powder level drops, providing different levels of mixing and temperature uniformity of the powder bed. Achieving the best induction time can be expected to remove a higher portion of fines from the powder bed leaving the larger particles to be melted which require more energy. Having a proportion of smaller particles in the powder bed during the melting stage can be advantageous as it can aid the heat transfer between the remaining larger particles.

5.2 | Melting stage

The recorded time taken for all the powder to adhere to the mold wall for 30% and 10% powder fills is shown in Figure 11. Results show that the constant speed that



(a) 10% Powder Fill (b) 30% Powder Fill

FIGURE 11 Effect of rotational speed on combined induction and melting time caused all the polymer to adhere to the mold wall in the shortest time was 15 RPM for 30% and 25 RPM for 10% powder fill level. This comparison highlights the effect of powder flow, with the expected trend that increasing the rotational speed for lower filling level allows the powder to circulate more effectively to improve heating cycle time.

The IAT during the complete rotational molding cycle for a range of speeds is shown in Figure 12. For all of the completed tests, the cooling system was activated when the IAT reached 200°C. It is found that during the fusion stage of the heating cycle, the temperature traces begin to converge as the internal temperature reaches its peak before cooling begins. As the fusion stage starts at different time periods for different rotational speeds, the degree of cure (DoC) was found to alter with rotational speeds tested. By altering the PIAT to balance the DoC, the cycle time could be further reduced with no effect on the mechanical properties of the product.[38] A complete set of results for 10% and 30% are shown in Table 3.

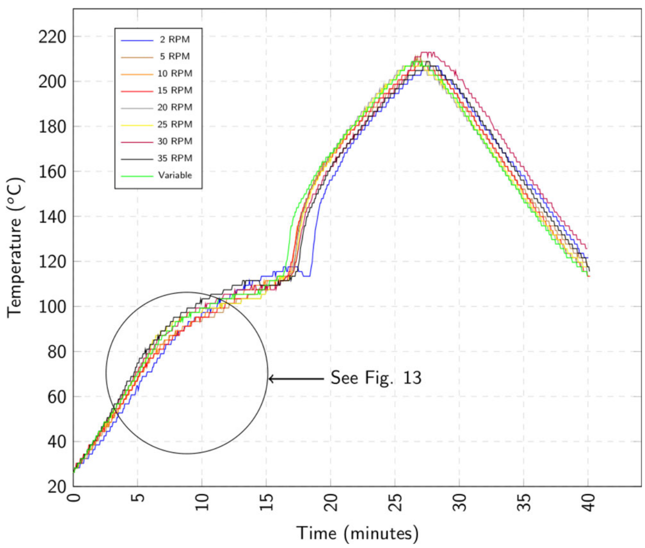


FIGURE 12 Effect of rotational speed on internal air temperature within a uni-axial cylinder for a rotational molding cycle (30% powder fill) [Color figure can be viewed at wileyonlinelibrary.com]

5.2.1 | Varying speed

Using the results from constant speeds as guidance the speed was varied throughout the heating cycle. 20 RPM was chosen for the induction stage as it provided a strong circulation regime at the induction stage. As the powder begins to adhere to the mold wall, it was observed that the increased presence of cohesive and frictional forces caused the powder to flow in a more chaotic manner. At this point, the rotational speed was reduced to 10 RPM (see Figures 13 and 14) as it was observed to maintain a more steady circulating flow motion than at 15 RPM. The rotational speed was then increased to 25 RPM as the powder level dropped and was observed to be flowing in a slumping manner (which is not useful). Increasing the rotational speed to 35 RPM rather than 25 RPM was also tested. However, at this speed, a longer time was needed for all of the powder to adhere to the mold wall despite no obvious change in powder flow being observed. This highlights the complexity of optimizing the heat transfer within the rotational molding system with a balance between powder temperature uniformity and heat transfer from the mold wall that is required.

It was found that altering the rotational speed to allow the powder bed to be more efficient with the heat energy within the system can reduce the heating time required to adhere all powder to the mold wall by up to 2.5%. This was found by comparing the total time of the

TABLE 3 Induction and melting time for range of rotational speeds

	Induction time (min)		Melting time (min)	
Rotational speed (RPM)	10%	30%	10%	30%
2	6.4	9.5	4.6	9.2
5	6.2	8.1	4.1	9.2
10	6.3	7.8	4.1	9.1
15	6.2	7.4	3.9	9.3
20	6.3	7.2	3.7	9.9
25	6.3	7.8	3.2	9.5
30	6.3	7.8	3.4	9.7
35	6.3	7.9	3.6	9.7
Variable (20-10-25)	-	7.2	-	9.2
Variable (20-10-35)	-	7.2	-	9.5

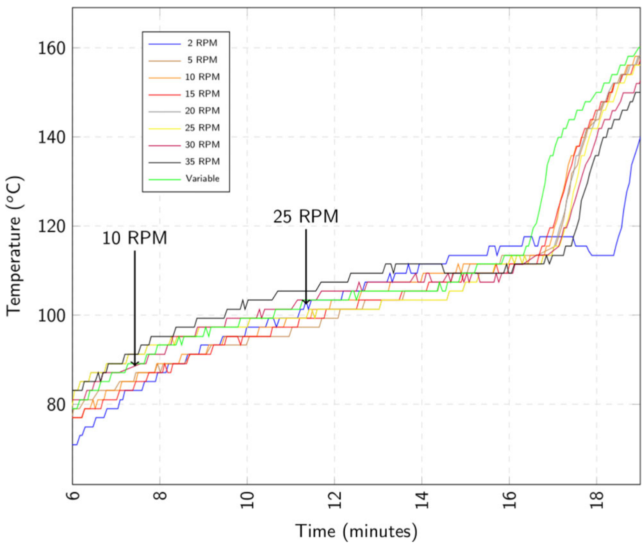


FIGURE 13 Effect of rotational speed on internal air temperature during melting stage (30% powder fill) [Color figure can be viewed at wileyonlinelibrary.com]

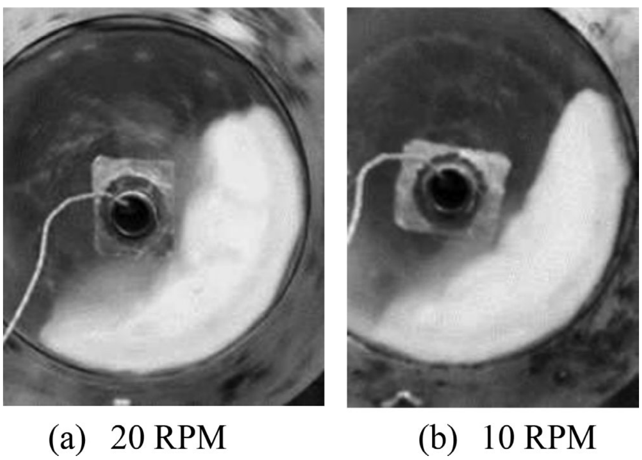


FIGURE 14 Effect of rotational speed on powder flow during melting stage

induction and melting stages for the constant rotational speed which provided the lowest average time (i.e., 15 RPM) against the variable rotational speeds. The rotational molding process hold many advantages over other polymer forming processes, such as blow molding and injection molding. However, a disadvantage of rotational molding is its long cycle times, which is restricting the industries growth. Finding opportunities to reduce cycle times is significant to the feasibility and growth of the rotational molding industry. Within the rotational molding industry, constant rotational speeds are commonly used. These findings show that there is scope for further cycle time improvements by varying the rotational speeds throughout the heating stage.

5.3 | Wall thickness uniformity

To investigate the effect of rotational speed on wall thickness uniformity, each molded cylinder was cut into 30 test samples (Figure 3). For each of the cylinders, the samples were taken from the same positions and numbered accordingly. As per the markings shown in Figure 3a, each molded cylinder was cut longitudinally into four parts with three of the parts measuring 60 mm in width. The three 60 mm width parts were then cut into ten further pieces with each of their circumferential positions shown in Figure 4. Thirty wall thickness measurements in total were recorded per cylinder and the SD of wall thickness measurements is shown in Figure 15.

Results show that the SD of wall thickness increases rapidly beyond 10 RPM for 30% powder fill and beyond 20 RPM for 10% powder. This result can be attributed to the powder flowing in a more chaotic and less uniform manner at these speeds, especially during the beginning of the melting stage. Interestingly, for both 10% and 30% powder fills there is a steady reduction in the standard deviation between 2 and 10 RPM. This trend was also found by Walls[6] and contributed to the fact that as the rotational speed increases the powder is laid up more gradually because the powder bed is in contact with the mold surface for shorter periods of time and therefore should overall produce a more uniform wall thickness. However, these results were found to also correlate to the powders flow and position being observed during the melting stage. Increasing the rotational speed from 2 to 10 RPM was found to provide a more constant position of the powder, which can be correlated to the improved wall thickness uniformity. By further increasing the rotational

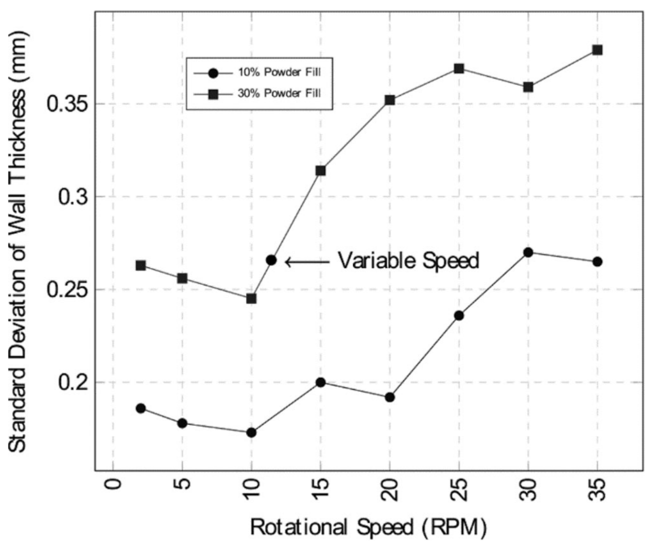


FIGURE 15 Effect of rotational speed on wall thickness uniformity

speeds, the powder is seen to flow in a more chaotic (less consistent) manner which corresponds to the reduced wall thickness uniformity found at these speeds.

For the case of the variable speed at 30% powder fill (see Figure 15), the SD of wall thickness was found to be 0.27 mm. This is found to be lower than the constant speeds tested above 10 RPM which is an interesting finding as speeds above 10 RPM were used during the variable speed cycle. This highlights that it is at the start of the melting stage which has the biggest influence on the wall thickness uniformity as this is when 10 RPM was used for the variable speed cycle.

Existing research literature does suggest that the wall thickness uniformity is affected by rotational speed.[5,39] However, the relationship between the powder flow schemes (caused by altering rotational speed) and the wall thickness uniformity has not been previously investigated.

The cylindrical mold is heated by two electric heating elements (illustrated in Figure 2b) which are attached to the mold and therefore rotate together with the mold. Analysis of the wall thickness measurements around the circumference of the cylindrical mold showed a noticeable reduction in wall thickness of up to 7% at the areas where the two heating elements meet (Figure 16). This finding highlights the challenge of utilizing electrically heated molds to achieve a uniform supply of heat to all areas of the mold as well as the effect of temperature deviations on the wall thickness distribution. Figure 17 shows the inner mold wall temperatures of an empty mold after 5 min of heating. Positions 1, 5, 6, and 10 were found to have the lowest temperatures, which correlates strongly to lower average wall thicknesses at these positions (Figure 16). Heating the mold in a convectional oven environment can be an easier method to achieve improved uniformity of heat transfer to every part of the mold but is significantly less energy efficient.

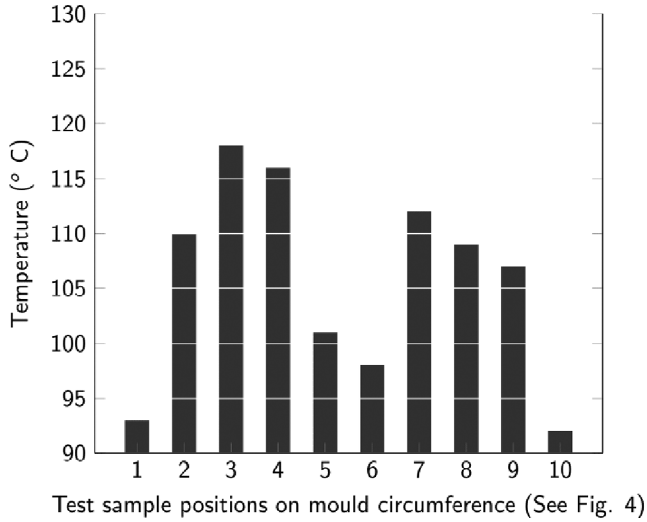


FIGURE 17 Temperature of inner mold across the circumference of molded cylinder

5.4 | Part strength and quality

Samples were tested for impact strength as per the standard BS EN ISO 6603-2:2000 (see Figure 18). For total impact strength, minor deviations were found between the different rotational speeds tested. No strong correlation was found between the rotational speeds although the lowest strength was recorded at the highest rotational speed tested (35 RPM).

A visual inspection of all samples showed no clear difference in appearance or surface quality for the range of rotational speeds tested.

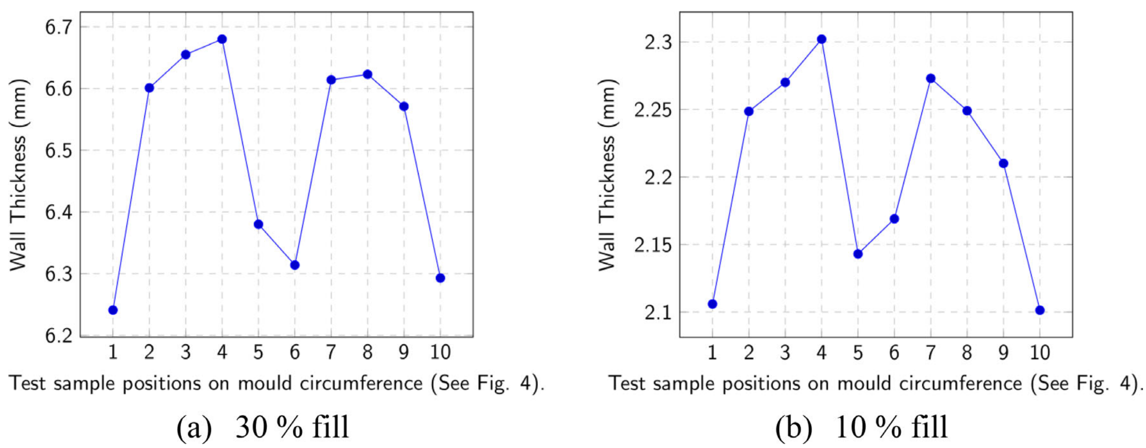


FIGURE 16 Average wall thickness across the circumference of molded cylinders [Color figure can be viewed at wileyonlinelibrary.com]

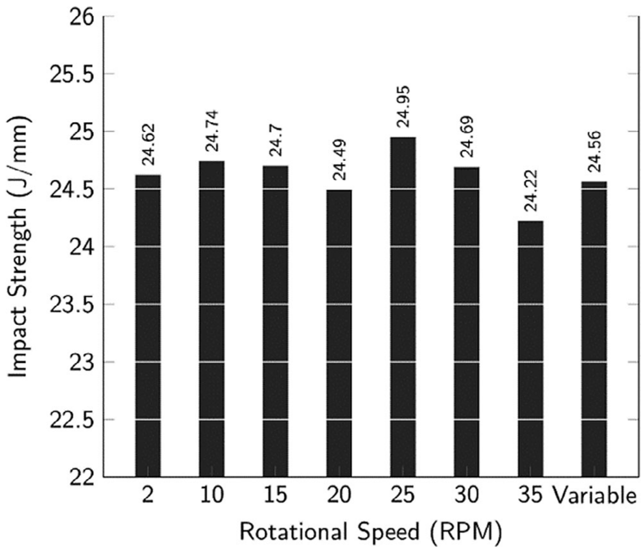


FIGURE 18 Total impact strength (30% fill samples)

6 | CONCLUSIONS AND FUTURE WORK

In this article, the effect of rotational speed and powder fill level for rotational molding were investigated for a cylinder mold under uniaxial rotation. This research is the first to open a new avenue in optimizing speed control for rotational molding based on an understanding of powder flow.

Results provide guidance on selecting suitable constant rotational speeds based on the desired wall thickness (powder fill). The shortest adhering time of the powder was found to occur at different rotational speeds depending on the powder fill with an increased rotational speed optimum for 10% powder fill when compared to 30%. Testing results prove that changing the rotational speed parameters during the rotation molding cycle can provide both time savings of up to 2.5% and control over the wall thickness uniformity. Industry today is facing a resource scarcity with many companies under pressure to be more energy efficient and varying the rotational speed has the potential to provide energy savings.

The change in wall thickness uniformity found with changing rotational speed highlights that caution must be taken when going beyond 10 RPM. The trend seen between rotational speed and wall thickness uniformity was first time correlated to the powder flow at these speeds.The deviation in wall thickness from the moldings in relation to the position of the heating elements highlighted the difficulty in using electrical heating elements for rotational molding as it can be difficult to avoid "cold spots" and provide a uniform heat supply to all areas of the mold.

The work presented in this article is limited to uniaxial rotation of a cylindrically shaped mold. Future work will develop this to biaxial rotation and beyond for a range of mold geometries. This will enable a better understanding of how the additional degrees of rotational freedom (which become possible when using a robot arm) can be best used to improve molding efficiencies with better processes (e.g., improved cycle times, wall thickness distribution, energy consumption, etc.).

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