Advanced process control in robotic rotational moulding

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Advanced Process Control in Robotic Rotational Moulding

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Abstract

Rotational moulding is an extremely important industrial process used in the manufacture of hollow plastic products in large and small dimensions. The basis of this process is heating and tumbling the polymer powder with a heated mould, then the polymer becomes tacky and adheres onto the inside of the mould to form the designed shape. It is a very effective and economic way for manufacturing hollow plastic products, but the process is inflexible with an exceedingly long cycle time. In the early years, rotational moulding was mostly based on trial and error, but recent research and industrial application introduced in-mould sensing and simulation which gives a better understanding of the moulding process. However, compared with other plastic forming technologies, these developments have fallen far behind. The only controls lie on the temperature and oven time, as well as the limited variation on rotational speed, which leads to the simplicity of this process. This nature probably hindered the further development of the rotational moulding process. The latest developments in mould, motion platform and simulation created a new angle for rotational moulding to embrace automation and intelligent technology. Firstly, the convection oven is being replaced by moulds containing internal heating and cooling elements. Secondly, the simple two-axis rotating arm is being replaced by programmable multi-axis robot arms. Thirdly, process simulation has been extended from the heating and forming process to the cooling down and deformation phase. The absence of ambient high temperature during the heating phase allows multiple sensors to be installed, which are not economically possible in the traditional rotational moulding condition. Thermocouples, pressure sensors, in-mould camera and ultrasound have been integrated as live monitoring systems. The industrial robot provides a mature programmable and integrable platform for sensing and control. The expanded simulation gives a more precise prediction of the whole production process. A preliminary study at Queen's University Belfast shows that this prototype robotic rotational moulding system can clearly reduce the cycle time and hugely increase energy efficiency. Ongoing tests are being conducted to assess the full capability of this new system. Simulation results and data collected from the sensors together with the robotic control system enable instant control on mould temperature, pressure, position, motion, speed and even cooling rate. Together these complementary technologies are creating an entirely new form of rotational moulding that is highly flexible and controllable, and which offers the prospect of a step-change in rotational moulding technology. It is possible to match the zonal temperatures and mould movements to suit a particular product design and for different stages of the production cycle. Additionally, the closed-loop control system coupled with a fully programmable system lays the foundation of the smart manufacturing system where control parameters are optimised by iteration.

Key Words: Rotational moulding, Robomould, Process control, Robotics.

1. INTRODUCTION

Rotational moulding, also known as rotomoulding is an extremely important and relatively simple industrial process for manufacturing hollow plastic products in large and small dimensions. Nevertheless, compared with other plastic forming technologies like injection moulding, blow moulding, compression moulding, and thermoforming, to name a few, the development of rotational moulding has fallen far behind. Historically, the limitation of this process shifted from available materials to the restrained controls through the temperature and oven time, as well as the limited variation on rotational speed. This nature probably hindered the further development of the rotational moulding process. The latest developments in mould design, machine platform and simulation create a new angle for rotational moulding to embrace automation and intelligent technology.

Although successful cases of advanced process control of rotational moulding can be found from some company statements, there are very few scientific publications focused on studying the actual merits brought by these technological advantages. This paper provides a brief review of the development of rotational moulding, as well as the recent advanced process control technologies applied in the rotational world. A further discussion on the robotic application for advanced process control is the main focus of this paper.

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2. LITERATURE REVIEW

2.1 Rotational Moulding

The first approach for modern rotational moulding was reported as ‘Slush Moulding’ back in the 1930s, by using polyvinyl chloride (PVC) plastisol to coat the inner surface of a heated hollow mould. Due to the material and technology limitation, this moulding process was only recognized as an industrial plastic forming method in the late 1950s. Followed the improvement of polymer and the advent of process control, the rotational moulding industry has embraced constant growth since then (Roy J. Crawford & Kearns, 2012).

Rotational moulding (Fig.1) involves the external heating of a thin-walled hollow metal mould containing a polymer powder. Heating occurs while the mould is rotated multiaxially. The powder melts and coats, or sinters, onto the interior wall of the cavity. The mould is then cooled, which allows the part to solidify and crystallize in the case of crystalline plastics. Finally, the part is removed and the mould is charged to repeat the cycle(Roy J. Crawford, 1996). Fig.2a shows a typical Ferry Rotospeed rotational moulding machine with a convection oven and cooling station.

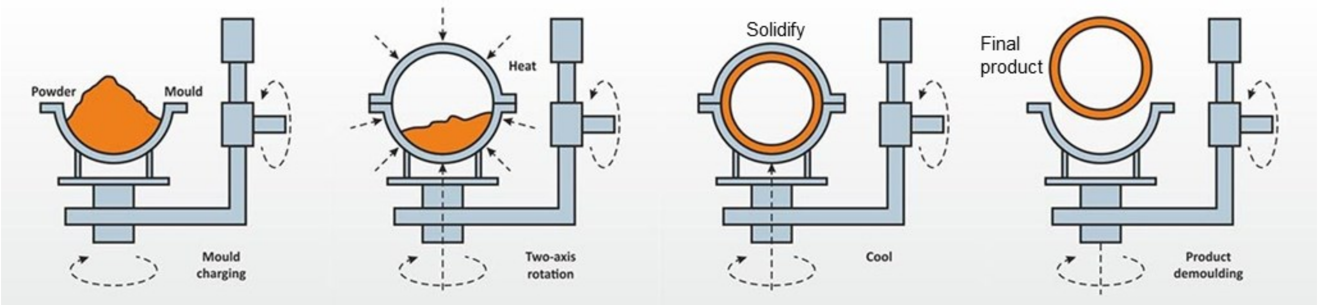

Fig. 1 Schematic of Rotational Moulding (YANGKANG, 2020)

With the advantages of low cost and design flexibility in shape, type and scale, a large number of materials have been developed for rotational moulding, such as polyethylene (PE), nylon, Acrylonitrile Butadiene Styrene (ABS), High Impact Polystyrene (HIPS), polypropylene, Ethylene-vinyl acetate (EVA), and even reactive materials as polyesters, silicone rubbers, polyurethanes and polyamides (Wypych, 2012). Rotational moulding products reach almost every market from simple bulk storage containers to sophisticated automotive, medical and aerospace applications. Advantages of rotational moulding include the process is not pressure dependant, low orientation levels in mouldings with a small shear rate in polymer, relatively simple process control, inexpensive moulds and machines. On the other hand, the material is heated and cooled in the same mould implies some poor thermal efficiency of the process, leading to longer cycles. Prior to processing, materials are required to be reduced to powder by grinding or pulverizing for some solid polymers (Nugent, 2017).

In each of the production cycles, both the polymer and mould must be heated from room temperature to above polymer melting temperature and subsequently cooled to room temperature. The rotational moulding process suffers a considerably long cycle time with long heating and cooling time and extra energy consumption, which impedes more widespread growth of the process. For the heating process, various heating measures including oil heating, electric direct heating, electric infrared heating, microwaves, induction heating have been developed, however, the most common commercialized method is convection oven using propane or natural gas combustion (Roy J. Crawford et al., 2002).

More research was carried out for the cooling process, since cooling could affect the final product property and cooling time is relatively long due to the poor thermal conductivity of plastics. Although rapid external cooling by forced air, water spray or shower is possible, internal cooling rates are the major hindrance. Various internal cooling procedures were studied by a large number of researchers(S.B. Tan, P.R. Hornsby, M.B. McAfee, 2006). Cryogenic CO_2 and N_2 were introduced as the internal coolant (Khouri, 2004; O’Neill, 1999b). However, a direct supply of cryogenic liquid resulted in surface damage illustrated by wrinkles at the moulding base due to the cold shock. Although a study achieved cut the cycle time by 14% by using compressed air operated by air movers, the product formed wrinkles caused by high-speed airflow. Delayed internal cooling was proposed by O’Neill (O’Neill, 1999a), McCourt and Kearns (Mccourt & Kearns, 2009) to avoid the cold shock, however, this method has limited saving on the cycle time. Tan found that water spray produced by an ultrasonic nozzle achieved a high cooling rate directly from the melt with an acceptable internal surface quality (Tan, 2010). Besides, the cooling rate also affects the morphology, shrinkage, warpage, and properties of the product. In general, rapid and symmetrical cooling across the mould results in smaller spherulite size, increased mechanical properties and less potential warpage or distortion in mouldings (S.B. Tan, P.R. Hornsby, M.B. McAfee, 2006). Queen's University Belfast and a German moulding company Maus together developed an internal cooling device called RotoCooler (Fig. 2). A follow-up study confirmed the benefit of using internal water spray by reducing cycle time and improve product property when applied at the right internal air temperature (Wilson, 2014). However, RotoCooler has not been widely applied in the industry due to the complexity of installation and operation.

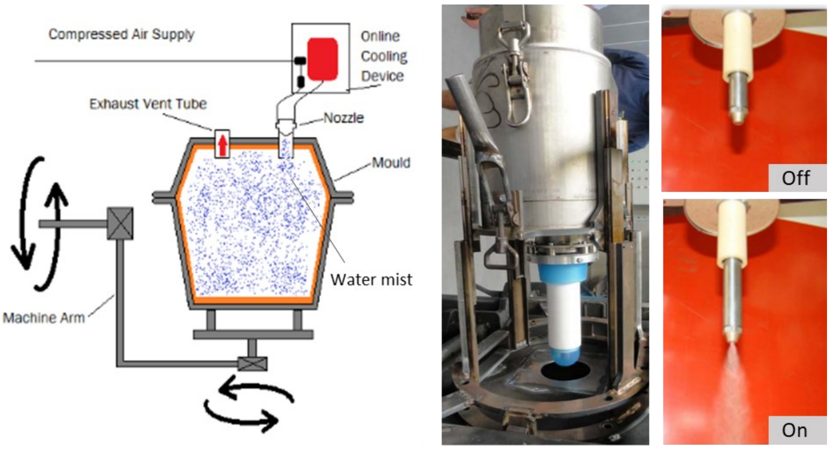

Figure 4. RotoCooler and principle of its internal cooling (Mark P. Kearns, 2014)

Apart from that, rotational moulding is a slow process with many quality specifications, requiring full-time attention from experienced operators to supervise and control the process (Rodrigues, Mendes, & Fonseca, 2004). It has been demonstrated that the most effective parameter for controlling the process is the temperature of the air inside the mould (Cramez, Oliveira, & Crawford, 2002). And due to the bi-axial nature of mould rotation, limited measurement techniques and equipment (Ramkumara et al., 2015) can be used for collecting cost-effective thermal data. Successful tools such as Rotolog™ have been applied for process monitor. Furthermore, the data-driven model predictive controller had been verified to be beneficial for rotational moulding with improved product quality(Garg, Gomes, Mhaskar, & Thompson, 2019).

2.2 Automation and robotics in rotational moulding

Compared with injecting moulding, thermoforming and blow moulding, there is a widely accepted lag behind on the technical development of rotational moulding. In traditional rotation moulding, high temperature and bi-axial motion impede the installation of instruments that help monitor and control the process. For a long time, the only control lied in the temperature and heating time. However, along with the expansion of this industry, advanced process control techniques were coming with new mould and machine designs (Roy J. Crawford & Kearns, 2012).

In recent years, industrial robots have been used in rotational moulding for auxiliary works. Customized robot cells were built for placing insert, drilling, trimming and flame processing (B. Adams, 2019; Rocklakerobotics, 2021). With the increased positioning accuracy and repeat positioning accuracy, post-processing can be carried out accurately and efficiently. The use of robots cuts the total cycle time and reduces hazards to the operators. The concept here is to maximize automation from the raw material feeding to the final part finishing.

An Italian company Persico developed an automated rotational moulding machine Leonardo in 2002 (ARMO, 2018). Leonardo is capable of automatically filling material, mould closing, heating and cooling cycle, and demould. To fulfil the automation, a direct tool heating technique was applied by using diathermic oil for heating. A later version called SMART (Fig.2b) was launched in 2011. SMART uses electric heating and has a much more compact machine size. It offers an automatic coupling docking system connecting all electrical, pneumatic and auxiliary services. SMART brought an optional intelligent spider recognition system that can recognize spiders and loads to match the moulding program('Smart Technology by Persico', 2021). Up to 42 mould temperature probes and 4 internal temperature probes can be installed. The heating elements are programmable and capable of zonal heating. Persico claimed these two machines could save 30% to 70% energy respectively.

The innovation of Persico brought the rotational moulding out of the hot oven and combines modern techniques into the process control. Another company from Belgium, Automation & Manufacturing Service (AMS), took a step further, integrated electric heated mould onto an industry robot arm. This cutting-edge machine has been named Robomould (Fig.2c). This is the first time a robot arm has been used to carry out the rotation motion for the moulding process. In comparison to the two-axis rotation and rock-and-roll motion, Robomould has a distinguish high level of flexibility on mould motion control. A giant slip ring is installed on the robot J6 axis, which allows the connection of heating elements, pressured air and other instruments. According to the introduction from AMS, Robomould cuts 90% CO_2 emission compared with a traditional convection oven (AMS, 2021). McCourt et.al. studied the heat efficiency of Robomould. They proved Robomould can save 22% heating time and approximately 15 times less heating energy for similar part quality over the convection oven (McCourt, Kearns, Martin, & Butterfield, 2017).

a. Ferry Rotospeed b. Persico SMART c. AMS Robomould

Figure 2. Different types of machines for rotational moulding

3. DISCUSSION OF THE POTENTIAL OF ROBOTIC ROTATIONAL MOULDING

3.1 Remote Monitoring

Giving the electric heating mould design, Robomould gets rid of the restriction of the hot oven environment. The inherent nature of the robot also provides a compatible integration platform. Those sensors that cannot survive the extreme temperature now can operate in an affordable environment. Temperature monitors like RotoLog and DataPaq can shed off the heavy and bulky insulator and work perfectly without adding additional weight to the mould. Pressure sensors are easier to install and can ease the safety hazard concern on the pressurized rotational moulding. Ultrasound detection can be integrated on the mould to provide live data on the part thickness and even for solidification and densification. In mould camera can be installed to monitor the powder flow, melting status, foaming in the case of foaming layer added, fibre distribution and embedment for fibre reinforced material. Not to mention that the prices surge for sensors capable of working in extreme temperatures compared with those work at room or mild high temperatures.

Unpublished initial research carried out by Alemán and Pritchard from QUB has shown that both the in-mould vision system and ultrasound system have the potential to help understand the powder-melt-solidification transformation, bubble formation and dissipation, and even inner surface quality. The Mould Surface Vision System can take photos and videos during the moulding process, providing live visual analysis of the moulding process, as shown in Fig.3a. Ultrasound waves are responsive to solidified part thickness Fig.3b. The moulding process can be monitored with high-temperature transducers. By analysing the sound reflection, characteristics as densification, part thickness, solidification, and demoulding timing could be obtained.

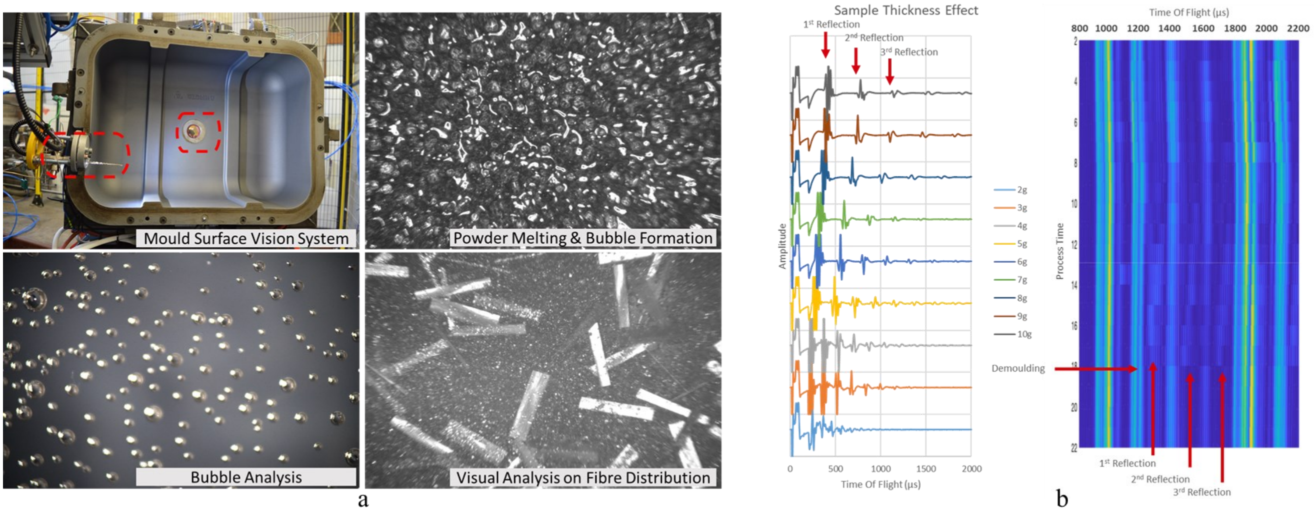

Figure 3. In-mould vision system (a) and Ultrasound technique application (b) (Courtesy of David Castellanos Alemán and Alex Pritchard from QUB)

3.2 Heating

Fast and accurate control of heating can be achieved on Robomould. In the case of a convection oven, the air is heated and forced to circulate in the oven, then the mould is heated by the hot air. There is an obvious time delay from setting the oven temperature to achieving the desired mould temperature. Robomould uses electric direct heating elements, paired with control from Programmable Logic Control (PLC) to communicate with the robot. Thus, the control of heating could be more accurate and timelier. In the past, the routine of rotational moulding was setting the oven temperature, putting the rotating mould in the oven and waiting for the internal air temperature to the peak. Very little control is available at this stage. Researchers had tried altering the oven temperature for different heating rates, but very few conclusions were drawn due to the restrained control (M P Kearns, Corrigan, & Crawford, 2000). Now, the output power of each heating element and the timing of on and off can be precisely programmed during the cycle. This research could be continued with the possibility of trying out accurate heating rates setting, even different heating rates during the different stages for heating the polymer. A faster and energy-saving heating sequence could be drawn out of this kind of study.

3.3 Cooling

Cooling is extremely critical to the final product property as well as total cycle time. Due to the poor thermal property of plastic, it takes longer to cool the condensed and solidified part than to heat the powder. Symmetrical cooling had been agreed to be beneficial for reducing cooling time and improving product property (R. J. Crawford & Throne, 2002; Mccourt & Kearns, 2009; S.B. Tan, P.R. Hornsby, M.B. McAfee, 2006). However, the complexity of devices and process control had prevented this technology from further industrial development. The Robomould integrated a gas-sealed slip ring, which allows the compressed air transferred to the moulding during processing. This technique will make the control of internal cooling easier. Without the complex air pipe installation on a rotational mould machine and insulation for a water container, Robomould may achieve better internal cooling compared with using the RotoCooler on a traditional machine. Another advantage is that the robot has a high location and relocation accuracy. Thus, an independent internal cooling device can be installed at the ‘cooling station’. Internal cooling can be achieved automatically by putting the mould against a stationary cooling pipe. Adding the merits of sensors into account, matching the external and internal cooling would be possible, which can potentially largely reduce the cooling phase time and improve the overall product performance.

3.4 Motion control

The motion control of rotational moulding has a big impact on the powder heating up, material distribution and product property. This moulding process uses relatively very low rotation speed as 4-20 RPM and follows the general speed ratio from experiments and experiences. Adam et al. reported that varying the rotational speed could reduce the heating time by improving powder mixing and temperature uniformity (J. Adams, Jin, Barnes, Butterfield, & Kearnes, 2021). The advantage of Robomould lies in the freedom and capacity of robotic motion.

Complex and accurate motion can boost the research on rotational motion control at a level never achieved before. It is possible to use fast and chaotic motion for quick powder mixing, smooth rolling and tumbling for best heating transfer and surface quality. In conjunction with the live monitoring mentioned above, the optimal motion, heating rate and timing could be achieved. Apart from that, the J6 axis of the robot can reach 60 RPM according to the operation manual. Crawford pointed out that centrifugal force helped improve product quality (Roy J. Crawford et al., 2002). However, with limited rotation speed on a traditional machine, the high rotation speed is not fully studied. By using Robomould, the centrifugal force could be taken into account for its impact at the different phases of rotational moulding.

3.5 Simulation

Another powerful tool worth mentioning is the recent development in simulation. Using the RotoSim as an example, it not just can simulate the powder pool during the heating phase, also reveals the heat transfer, distribution and even product shrinkage after demoulding (Seregar, McCourt, Kearns, Martin, & Menary, 2020). Ongoing work has been carried out to integrate the robot motion into RotoSim. With the help of simulation, different motions can be designed, simulated and experimentally verified. Powder distribution can be controlled at a much higher level, which means product thickness could vary to meet the design requirement. Heating and cooling study could be carried out on a much solid ground with an easier way. Complex products are possible to be rotational moulded even with less material consumption.

3.6 Pressurization

Last but not least, the sealed slip ring mentioned above also provides a possibility to further study the influence of internal air pressure on the rotational moulding. Applying both positive and negative pressure in the mould cavity at different stages can help to improve the product quality and reducing cycle time (R. J. Crawford & Throne, 2002). Pressurization helps the part to tightly contact the inner mould surface and speeds up the bulb dissipation, hence improves the heat transfer and reduces the time needed for removing bubbles. The vacuum works similarly when initially applied and then return to the atmospheric pressure. Improved monitor eased the safety concern on using the pressurized mould, out of oven environment and integrated air-tight system simplifies the process to applying pressure or vacuum, further exploration of the pressurization on rotational moulding can be performed for both academic and industrial application.

4. CONCLUSIONS

Robotic rotational moulding has very promising potential to fulfil the advanced process control requirement in this industry. These prospects are concluded below:

1. Easier sensor integration and remote control based on an oven free and compatible robotic platform.
2. Fast and accurate mould temperature control with electric direct heating and zonal control.
3. Accurate and symmetrical cooling is more achievable on a robotic rotational moulding system with internal cooling.
4. Complex mould motion can be achieved which allows new products design and new factors (such as centrifugal force) to affect the moulding results.
5. Robotic rotational moulding simulation will further improve product design and process control.
6. Pressurisation and depressurisation can be achieved.

FUTURE WORK

Robotic integration brings a wider view of rotational moulding. The combination of monitoring, heating and cooling, motion controlling, simulating and pressurizing can create countless possibilities. Further research plans are in place at Polymer Processing Research Centre and more results will reveal shortly.

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