Internal Cooling in Rotational Molding—A Review

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Rotational molding suffers from a relatively long cycle time, which hampers more widespread growth of the process. During each cycle, both the polymer and mold must be heated from room temperature to above polymer melting temperature and subsequently cooled to room temperature. The cooling time in this process is relatively long due to the poor thermal conductivity of plastics. Although rapid external cooling is possible, internal cooling rates are the major limitation. This causes the process to be uneconomical for large production runs of small parts. Various researchers have strived to minimize cycle times by applying various internal cooling procedures. This article presents a review of these methods, including computer simulations and practical investigations published to date. The effects of cooling rate on the morphology, shrinkage, warpage, and impact properties of rotationally molded polyolefins are also highlighted. In general, rapid and symmetrical cooling across the mold results in smaller spherulite size, increased mechanical properties and less potential warpage or distortion in moldings. POLYM. ENG. SCI., 51:1683–1692, 2011. © 2011 Society of Plastics Engineers

INTRODUCTION

Rotational molding is a process for producing hollow plastic articles. It is also known as rotomolding or rotocasting. The four basic steps in this process are, (i) charging of polymer powders, (ii) heating, (iii) cooling, and (iv) demolding [1]. Initially, the polymer powder at room temperature is charged into a metal mold. The mold is then rotated biaxially about two mutually perpendicular axes and transferred into an oven. Inside the oven, the rotating arm assembly is heated to above the polymer melting temperature. Subsequently, the mold is cooled to room temperature, before the part is removed from the mold. Polyethylene is the most widely used polymer in the rotational molding industry, representing about 80 to 90% of the total volume consumed [1–5]. Much of this review, therefore, focuses on this polymer. It has a relatively high thermal stability when stabilized, making it suitable for processing for an extended period in a high-temperature environment. Together with its relatively low cost, these are the main reasons why it dominates the rotational molding industry [2, 6]. Typical rotationally molded products include water and chemical tanks, kayaks, and road barriers. A typical cycle time for producing a 300 mm cube molding with 3 mm wall thickness in a carousel-type machine is about 30 min.

Conventionally, the cooling process in rotational molding is accomplished by forced air convection, external water spray cooling, and external evaporative cooling [7]. When only external cooling is applied, the heat must be conducted across the thickness of the polymer itself and subsequently through the mold, which is subjected to convection cooling on its external surface. Internal cooling is considered to be the most efficient way to enhance heat transfer rates from the molten plastics and achieve effective reduction in cycle times. Because unsymmetrical cooling in the conventional rotational molding process can result in part warpage, combined external, and appropriate internal cooling can reduce the thermal gradient across the part thickness. Symmetrical cooling at both sides of the mold also benefits physical properties such as shrinkage and warpage [8].

INTERNAL COOLING IN ROTATIONAL MOLDING

General

In 1983, Ramazzotti [9] was the first to report on the application of internal cooling to rotational molding. Several internal cooling methods were proposed including use of air, water, and cryogenic liquid carbon dioxide (CO_2). Varying degrees of success using internal cooling for rotational molding were achieved. However, no results were published.

Scott [10] carried out experiments using an open-ended cylindrical mold (250 mm diameter and 375 mm long) to

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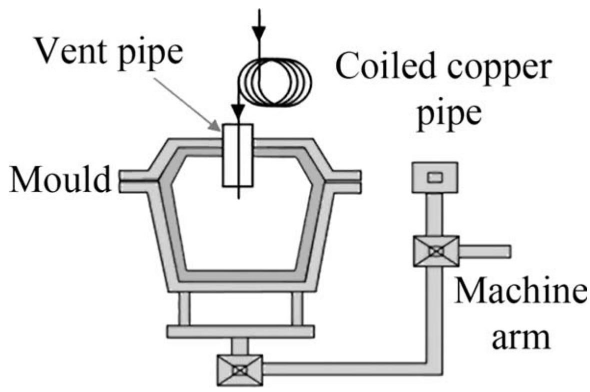

FIG. 1. Use of coiled copper pipe to bring in pressurized air into the mold.

observe the temperature gradient across the wall thickness of the part during the cooling stage. The inner molding surface was found to cool at approximately the same rate as the layer closest to the mold inner surface. As the inside surface of the molding was open, this facilitated heat transfer to the cooler air in the atmosphere. Therefore, some level of internal cooling was possible when cooling the mold with forced air convection, with one end of the mold open.

Sun and Crawford [11, 12] developed computer simulation software called ROHEAT to analyze the effects of internal heating and internal cooling. The powder layers were treated as a packed bed (no mixing), and the simulation was simplified to one-dimensional model, as the part thickness was very small compared to its surface area. Internal cooling was achieved by bringing cooled air into the mold cavity during the cooling process. The model confirmed the effectiveness of internal air cooling in shortening the cooling cycle and improving dimensional stability of moldings. Internal cooling resulted in a more uniform microstructure and a lower degree of warpage. Nevertheless, a method for achieving internal cooling during the actual process was not optimized.

Using a two-dimensional slip flow model, Ianakiev and Lim [13, 14] studied the efficiency of applying internal cooling to the rotational molding process for part thicknesses up to 12 mm. They demonstrated that combined external–internal cooling significantly reduced the cycle time, particularly for these thicker wall sections. They also showed that there were negligible differences in the cycle times between the early-onset and late-onset part warpage for the external–internal cooling method.

Compressed Air

Crawford and Tisdale [15] investigated two practical methods for achieving internal cooling to reduce cycle times in rotational molding. In the first method, a coiled copper pipe (8 mm inner diameter) was used to convey pressurized air into the mold (Fig. 1). The vent consisted of two concentric pipes to allow air into the mold via a central pipe and then exhaust through the outer pipe. As the coil was external to the mold, it was subjected to the prevailing external temperature conditions in the oven and cooling bay. During the cooling cycle, the air passing through the pipe in the cooling bay was cooled, and the cold air would thus cool the inside of the mold. In the second method, an air amplifier was used to pump air into the mold (Fig. 2). Similarly, a vent that consisted of two concentric pipes was used. The air amplifier was attached to the inner pipe while the outer pipe was used for exhausting air. For the first method, a reduction of 9% in the total cycle time was achieved when compressed air of 0.1 MPa (1 bar) was supplied into the mold via a 3.5 m long coiled copper pipe. In the second method, a 17% decrease in total cycle time was attained with 0.1 MPa (1 bar) compressed air supply to the air mover.

Van Uffelt [16] investigated internal mold cooling by applying compressed air. A pressure control vent of concentric pipes was used to monitor the pressure of the air entering the mold to achieve internal cooling. The compressed air was run through the machine arm to an automatic-opening, pressure reduction valve installed on the mold. The purpose of the valve was to avoid damage to the product's inner surface. Hot air in the mold was allowed to leave the mold via a second evacuating pipe in the mold to avoid generation of any excess pressure inside the mold. An attempt was made to balance the effect of internal and external cooling to achieve the highest temperature in the middle of the product wall thickness, to reduce warpage in the final part. A reduction of 30% in total cycle time was obtained.

Crawford et al. [17] found that cycle time could be significantly reduced using an air mover to enable internal heating and cooling. However, Khouri [18] stated that the reduction in cycle times achieved by Van Uffelt [16] and Crawford et al. [17] may be misleading because they were achieved by comparing the measured internal air temperature (IAT), which was directly affected by either the hot or cold air that was supplied into the mold, rather than the material temperature.

O'Neill [19] used Ringjet air movers to convey air into and out of the mold to achieve internal cooling (Fig. 3). The compressed airline pressure used was 0.2 MPa

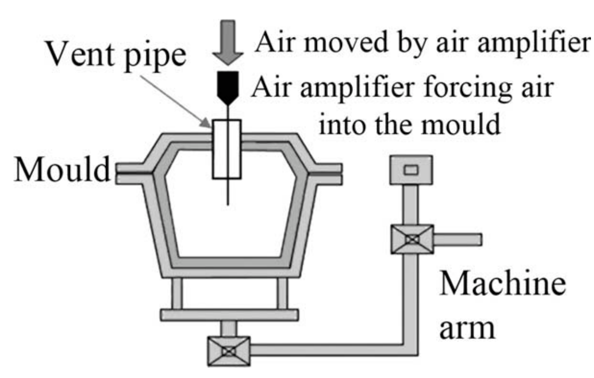

FIG. 2. Use of air mover to pump air into the mold.

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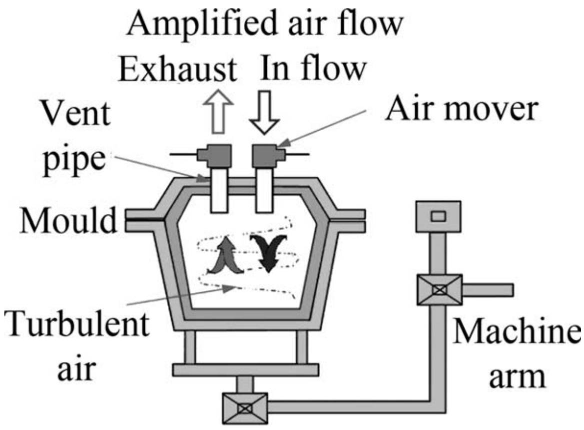

FIG. 3. Use of two air movers.

(2 bar). When internal cooling was applied, there was an immediate effect on the IAT, which could not be used as a means of control. Instead, a thermocouple was placed at a distance of 5 mm from the inside surface of the mold, at the inner surface of the part. Direct comparison of IAT for cycles with internal air cooling against cycles without internal air cooling was not possible due to masking of the thermocouple created by the airflow inside the mold. With internal air cooling, the cooling rate was higher. A saving of 13% in the cooling and 7.5% in the overall cycle time was obtained compared to normal molding.

In the EU-funded project known as "Intelligent Process Control for Rotational Molding" (2001), various aspects of the rotational molding process were investigated to enhance process control and, thereby, reducing cycle times [20]. A series of internal cooling trials were conducted using a deep-cooling system, which could constantly deliver extremely dry compressed air at very low temperatures, below −45°C, into the mold cavity (Fig. 4). Water spray was also applied externally to the mold when the internal mold cooling was introduced. More than a 50% reduction in cycle time was achieved using this system, known as Bekoblizz, compared to the conventional external forced air cooling. Nevertheless, the extent of this improvement may not be valid as the cycle time was again computed from the internal air temperature. The measurement of internal air temperature was directly affected by the internal cooling due to masking of the thermocouple. Introduction of low-temperature air at −45°C to the mold interior reduced the warpage compared to external water cooling in isolation. As much as 74% reduction in warpage was observed [21].

McDowell [22] also investigated internal mold cooling using an air mover with compressed air supplied through the machine arm. A reduction of 24% in overall cycle time was achieved as a result of a combination of the different techniques tested via mold preheating up to 100°C, powder preheating up to 85°C, internal mold cooling, and mold pressurization.

Khouri [18] used air amplifiers to improve heat transfer during the cooling stage by introducing air turbulence. Two air amplifiers were used, one to provide air into the mold and the second to exhaust air from the mold in an attempt to create turbulence and avoid pressure build up inside the mold. As measurement of the internal air temperature thermocouple was directly affected by internal cooling giving misleading information, the temperature of the inner plastic surface was considered for comparison purposes. In the internal cooling experiments, two different air flow rates were applied by varying the compressed air pressure to the air amplifiers conveyed through a pipe network of 15 mm diameter copper pipes. For Trial A, the velocity of the supply airflow used was 18 l/s (3.6 m/s), and the exhaust airflow velocity was 12 l/s (2.4 m/s). The compressed air pressure was 0.1 MPa (1 bar) for both amplifiers. In Trial B, the velocities of supply airflow and exhaust airflow were 25 l/s (5 m/s) and 16 l/s (3.2 m/s), respectively. The compressed air pressure was 0.2 MPa (2 bar) for both amplifiers.

Reductions of 19 and 11% in cooling and overall cycle time were obtained for Trial A compared to a normal molding cycle and corresponding reductions of 25 and 14% for Trial B. Doubling the compressed air pressure supply to the air amplifier (0.2 MPa in Trial B) to (0.1 MPa in Trial A) did not result in similar reduction in cooling time; however, as greater friction was produced inside the compressed air pipelines and at the inlet of the air amplifier, which was found to limit the air flow rates through the air amplifier into the mold [18].

In conventional rotomolding, the heat transfer coefficient between the polymer melt and the internal air is only 0.25 to 0.30 W/m^2 K [18]. Introduction of forced air inside the mold increases the heat transfer coefficient between the plastic and internal air and resulting in higher cooling rates. When estimating the heat transfer coefficient between air streams provided by air amplifiers and plastic, an analogy with gas jet impingement heat transfer was made by Khouri [18]. It was estimated that the variation in air temperature did not have a significant effect on the average heat transfer coefficient. However, the heat transfer coefficient was reduced by 43% when the distance from the stagnation

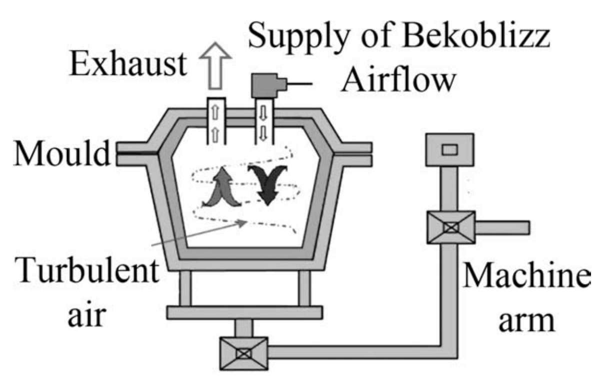

FIG. 4. Bekoblizz internal cooling apparatus.

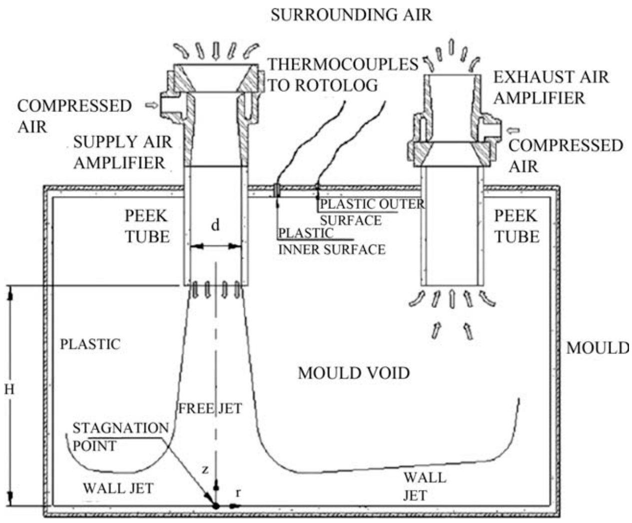

FIG. 5. Schematic diagram of the air amplifiers set up illustrating the air movement for internal cooling.

point (transverse direction) was increased to 175 mm away from the centre of air jet (Fig. 5). The heat transfer coefficient between the internal turbulent air and the surface from which the temperature was measured was estimated to be 50 W/m^2 K. The disadvantage of internal cooling using air movers was found to be the detrimental effect on the molten plastic at the onset of cooling, where high speed of the supplied air and the short distance between the amplifier exit and the molten plastic surface could cause wrinkles at the bottom of the molded parts.

More recently (2009), Abdullah et al. [23] demonstrated a cycle time reduction during rotational molding using a combination of physical techniques including (i) surface enhanced mold (adding pins or rough elements to the mold external surface), (ii) internal mold cooling by employing two air amplifiers (0.2 MPa air pressure), (iii) internal mold pressure (2.4 kPa), (iv) external cooling (external forced air of 3.78 m^3/s for first 3 min, external water spray at 10 l/min for 10 min and then external forced air of 3.78 m^3/s for 10 min) and (v) increased oven circulation fan flow rate (from 3.78 to 5.67 m^3/s). Using a combination of these techniques, an overall cycle time reduction as high as 70% was reported. However, they highlighted two issues from their investigation. First, the cycle time was computed from the internal air temperature traces, which were directly affected by the supply of cooling air from the air amplifiers. Second, the molded products exhibited high level of warpage. They also observed the wrinkling effect, mentioned earlier at the interior surface of the molded base, resulting from the high air velocities applied during internal mold cooling.

Cryogenic Liquid Nitrogen

O'Neill [19] used cryogenic liquid nitrogen (N_2) to accelerate external and internal cooling by applying two approaches. First, the nitrogen was pumped into the cooling bay environment to decrease the temperature of the cooling chamber and thus the air, which was circulated onto the mold using air movers. This was achieved by pumping cryogenic nitrogen through a copper pipe into the cooling bay where it was exhausted through a series of holes in a copper pipe ring during the cooling period (Fig. 6). The mold was rotated normally, and no other cooling was applied apart from internal air cooling using air movers. By this means, there was no significant increase in cooling rate and because only external cooling was achieved, this increased the cooling gradient across the molding.

In the second method, cryogenic liquid nitrogen was used directly to accelerate internal cooling through the induction air amplifier in place of the compressed air shown in Fig. 7. It was expected that when the nitrogen "drove" the amplifier, the incoming air would evaporate the nitrogen and thus create an extremely low temperature inside the mold cavity. As N_2 was supplied from a pressurized cylinder connected directly to the internal cooling equipment, the mold was not rotated. Direct supply of N_2 into the mold showed an immediate effect on IAT. The IAT dropped to zero in just a few minutes. The temperature did not drop any faster because the temperature of the internal cooling apparatus had been raised during the heating cycle and required cooling first before the inner air could be cooled. The actual temperature of IAT at values below 0°C was unknown as the temperature logging device was not suitable for low temperature applications. The dramatic decrease in IAT as a result of N_2 was not reflected on the internal surface temperature of the part. The main effect seen was at the internal surface of the mold. This implied a corresponding increase in the cooling gradient. In the experiment, the external mold temperature decreased at a faster rate than the internal plastic temperature. The author pointed out that it could be due to the frosted layer on the external mold surface. Because the mold had a higher thermal conductivity than the plastic, the external mold surface cooled more quickly. Further-

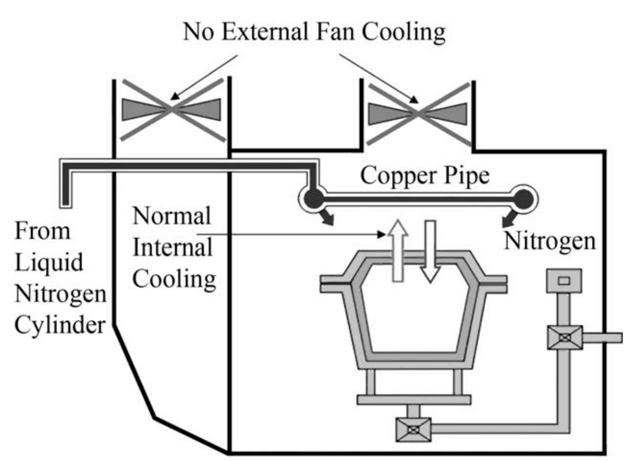

FIG. 6. Liquid nitrogen is pumped into the cooling bay and cold air is circulated into the mold via air movers.

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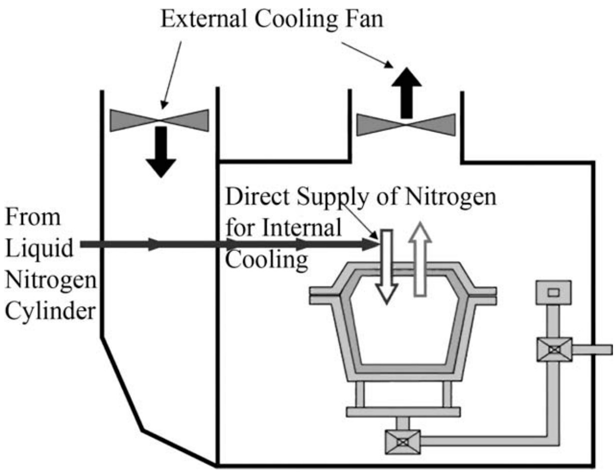

FIG. 7. Liquid nitrogen is supplied to the induction air mover and compressed air is supplied to the exhaust air mover, mold in stationary.

more, this approach to internal cooling caused a high degree of warpage and porosity in the moldings, which were generally more pronounced due to the decrease in internal mold pressure caused by the rapid cooling of the air in the presence of the cryogenic nitrogen [19].

Impact strength was found to increase with cooling rate, regardless of external cooling conditions. Internal cooling also reduced the level of molding shrinkage in the product, by up to 1.5% for 3 mm thick parts and 0.5% for 5 mm thick parts. However, use of liquid nitrogen was an extreme case and resulted in little control due to violent evaporation on boiling of the nitrogen. The nitrogen entering the mold was moving at high flow rate, and the velocity of nitrogen caused a rippling effect on the inner surface of the part, which was due to the supply of the coolant at an early stage after peak internal air temperature (PIAT) when the melt was very soft. O'Neill [19] stated that an ideal system would be to cool the internal air sufficiently first, without turbulence, to solidify the inner part surface and then continue to purge the internal volume of the part with coolant.

Cryogenic Liquid Carbon Dioxide

Khouri [18] applied cryogenic liquid carbon dioxide to achieve internal cooling. An auxiliary arm was designed and installed in the cooling chamber to allow the transfer of coolant from a stationary source to the biaxially rotating mold. Two rotating unions (rotating joints) were used to facilitate the rotation of this auxiliary arm in two perpendicular axes. The most important and also the most difficult and time-consuming task was to locate and install the auxiliary arm to match its alignment with the correct related position on the original arm to maintain consistency in rotation and to avoid movement. All pipelines inside the auxiliary arm or outside it and the stationary part of the rotating unions were thermally insulated to minimize heat transfer from their surroundings.

For internal cooling using liquid CO_2, the gas was supplied to the mold directly from two cylinders via the auxiliary arm. The liquid CO_2 was stored inside cylinders at very high pressure, about 5 MPa (50 bar) at 22°C. Because use of CO_2 at this pressure was not feasible, each cylinder was provided with a multistage pressure regulator to decrease the pressure to approximately 0.6 MPa (6 bar). The temperature of CO_2 at 0.6 MPa was 40°C subzero (−40°C). As even a pressure of 0.6 MPa was considered very high for rotomolding, a nozzle with a slot opening was used at the inlet to the mold. By this means, the nozzle not only reduced inlet pressure to a more acceptable level, but reduced gas temperature even further. The slot opening at the nozzle outlet was also designed to achieve better CO_2 distribution throughout the mold void [18].

For safety reasons, two 25 mm diameter polyetheretherketone (PEEK) tubes were incorporated to act as pressure release vents. Chilled water was circulated through the auxiliary arm to reduce the amount of heat absorption by the liquid CO_2 passed through the arm. It took between 2 and 4 min to connect the auxiliary arm. The temperature of the inner plastic surface was measured for comparison between molding trials [18].

The effect of CO_2 was insignificant in reducing cycle times. Although the plastic was cooled at higher rates at the beginning of the cooling period, the situation could not be maintained for several reasons. First, during the first few minutes of cooling, the diaphragm of one of the pressure regulators ruptured and stopped working. One pressure regulator was used over the rest of the cooling period. Second, the very low temperature of the CO_2 causing the pressure regulators and the flow meter passages to freeze within a few minutes from the beginning of CO_2 injection. Third, while CO_2 supply started as a continuous flow at a rate of 2 l/s, with the onset of freezing, its flow became periodic giving inconsistent or no flow. Continuous flow of CO_2 only occurred for a few minutes at the beginning of the cooling period, which was insufficient to cool the plastic inner surface effectively [18].

It was suggested that further work should use appropriate storage outlets and pressure regulators to supply liquid CO_2 rather than pure gas, enabling improved pressure and flow rate control [18].

Chilled Water Coil

Khouri [18] also used a chilled water cooling coil to act as a heat sink inside the mold to accelerate internal cooling (Fig. 8), thereby, avoiding damage to the internal molding surface, as is the case with direct gas injection cooling methods. The coil was maintained at low temperature by utilizing a chiller with built-in pump to chill and circulate water through the coil. There were several limitations associated with this method. First, the size of the mold cavity could be a limiting factor for installing the copper coil. Second, there was a possibility of polymer

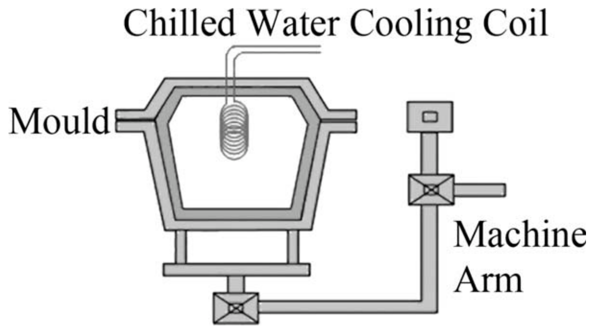

FIG. 8. Chilled water cooling coil.

build up on the coil during the heating stage. A third limitation was the selection of coil material to achieve efficient cooling. The coil was designed to have a surface area as large as possible, and chilled water was circulated through it.

There was a time delay of 120 sec before the auxiliary arm was connected and cooling began. During the time, the mold was only cooled externally by natural convection. During the heating cycle, the auxiliary arm components, including the rotating unions, were kept at low temperature by continuous circulation of chilled water. At the beginning of the cooling stage, the temperature of the chilled water, containing antifreeze solution, supplied to the coil was between -1 and -3°C. The inlet and outlet temperature of the water was estimated using thermocouples attached to the coil outer surface [18].

The temperature of inner plastic surface was used to compare cooling rates; however, the effects seen, here, were not very significant. A lower PIAT was seen because during the heating stage, the coil acted as a heat sink. However, the cooling coil did not damage the molding, because no forced air was supplied into the mold. It had been expected that the powder would stick to the cooling coil while it was in the oven. In fact, very little of the powder fell and melted on the coil surface [18].

Water Spray Cooling

Internal water cooling specifically offers high heat extraction rate to potentially reduce the cycle time significantly by making use of the latent heat of evaporation during the phase change. It cools the plastic directly from the inside of the plastic part to accelerate the cooling stage and also improve the part quality. Throne [24] compared the relative convective heat transfer coefficients for different cooling conditions. From Table 1, evaporating water is the most efficient cooling method.

In 2009, McCourt and Kearns [25–27] investigated the use of internal water cooling in rotational molding. A pneumatic nozzle was used to deliver an atomized water spray with an average droplet size of 50 μm into the mold. As soon as the mold came out of the heating stage, an insulated plate on the mold lid was removed, allowing an internal water spray to be applied manually for 40 sec. During this period, the mold remained in a stationary position. Subsequently, external water cooling was applied for the remaining of the cooling cycle. They managed to reduce the cooling time by 30% for a 3 mm part using a combination of internal and external water cooling, compared to the conventional external air cooling.

This study also demonstrated the potential of applying combinations of external–internal water cooling to reduce overall cooling time, especially if the internal water cooling time could be extended, and the need to remove the insulated plate from the mold lid could be overcome.

McCourt and Kearns [25–27] and O'Neill [19] also proposed that the internal cooling should only commence after the internal surface had solidified to avoid the unfavorable surface defects. However, by delaying internal cooling until the internal surface had been sufficiently cooled, there would be limited saving in cooling time. Tan et al. [8, 28] showed that atomized water spray produced using an ultrasonic nozzle achieved a high cooling rate directly from the melt with an acceptable internal surface quality. This work will be reported further in a subsequent communication.

Summary

The long cooling cycle in the rotational molding process is primarily due to the poor thermal conductivity of plastics limited further by the lack of internal cooling. Unsymmetrical cooling in conventional rotational molding often causes part warpage due to the thermal gradient evident across the part thickness. Ideally cooling should take place both externally and internally. As shown in Table 2, various internal cooling approaches were investigated experimentally. Compressed air and cryogens such as liquid N_2 and liquid CO_2 were applied to minimize the cycle time. The saving in cycle times reported by Crawford and Tisdale [15] (9 and 17%), Van Uffelt [16] (30%), Callan [21] (more than 50%), and Abdullah et al. [23] (70%) were all based on measurement of the internal air temperature. However, as internal cooling can directly affect the internal air temperature, it should not be used for the purpose of cycle time comparison. A better and more reliable approach is to compare the polymer melt temperature. Application of cryogenic liquids was not successful due to the complexity involved. Overall, Khouri [18] achieved the greatest saving in cycle time (14%) by applying

TABLE 1. The relative convective heat transfer coefficient values.

	Relative convective heat transfer coefficient values
Still air	1
Forced air	5
Still water	50
Flowing water	200
Evaporating water	1000

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TABLE 2. Experimental investigation of internal cooling in rotational molding.

Methods of internal cooling	Temperature measured	Finding
Cooling of open-ended mold	Polymer melt temperature	Some degree of internal cooling
Compressed air		
Supply of 0.1 MPa compressed air via a coiled copper pipe to the vent	Internal air temperature	9% saving in total cycle time
Supply of 0.1 MPa compressed air via an air mover to the vent	Internal air temperature	17% saving in total cycle time
Supply of compressed air into the mold via a pressure control vent	Internal air temperature	30% saving in total cycle time
Use of two air movers to supply compressed air (0.2 MPa) into the mold and exhaust	Polymer melt temperature	7.5% saving in total cycle time
Supply of compressed air via air movers combined with mold preheating, powder preheating and mold pressurization	Polymer melt temperature	24% saving in total cycle time
Two air movers to supply compressed air (0.1 MPa and 0.2 MPa) into the mold and exhaust	Polymer melt temperature	11% (for 0.1 MPa) and 14% (for 0.2 MPa) saving in total cycle time
Supply of compressed air (0.2 MPa) via two air movers combined with surface enhanced mold, internal mold pressure (2.4 kPa) and increased oven fan circulation flow rate	Internal air temperature	As high as 70% saving in total cycle time
Supply of extremely dry compressed air (-45 °C) into the mold	Internal air temperature	Over 50% saving in cycle time
Cryogenic liquid nitrogen		
Pump liquid nitrogen into the cooling bay and circulate cold air into the mold via air movers	Polymer melt temperature	Insignificant increase in cooling rate
Supply liquid nitrogen to the induction air mover and compressed air to the exhaust air mover (mold in stationary)	Polymer melt temperature	Inconsistent tests
Inject cryogenic liquid carbon dioxide into the mold	Polymer melt temperature	Inconclusive results
Install chilled water cooling coil inside the mold to act as heat sink	Polymer melt temperature	Insignificant effect on cycle time reduction

compressed air at 0.2 MPa (2 bars) for internal cooling via two air movers.

Although some saving in cycle time was achieved by applying internal cooling using the air movers, the supply of compressed air at high speed caused wrinkles on the inner surface of the molded part, the extent of this defect depending on the distance between the amplifier exit and the surface of molten polymer [18, 19]. Supply of cryogenic CO_2 at high speed from a nozzle directly toward the molten polymer at the beginning of the cooling period also resulted in surface damage illustrated by wrinkles at the molding base [18]. The use of chilled fluids for internal cooling also implied higher cost.

EFFECTS OF COOLING RATE

Morphology, Shrinkage, and Warpage

External cooling conditions have been shown to affect the density and degree of crystallinity of rotationally molded polyethylene parts [29, 30]. Quiescent-cooled samples gave the highest density and level of crystallinity followed by externally air-cooled samples and externally water-quenched samples [29]. Increasing cooling rate reduced both the percentage crystallinity and the spherulite size [30].

In general, the density, spherulite size, and level of crystallinity of the internal surface were higher than the external surface, reflecting the slower cooling rate in this region [29–31]. Largest spherulites were obtained from parts cooled in quiescent air. Slower cooling allowed the formation of more perfect crystalline structures and produced fewer nuclei than more rapidly cooled parts [30].

Part warpage is directly related to residual stress due to the locally varying strain fields during the solidification of polymer. In the conventional rotational molding process, the part is normally cooled from the external surface only. Temperature variations inside the material causes strain gradients and lead to an uneven residual stress build-up, which induces a bending moment in the part. The bending moment tends to warp the part to balance the residual stress [32, 33]. Increasing the external cooling rate will increase the unbalanced residual stress [32–35]. As a consequence, the induced bending moment and the part warpage also increase [32, 33]. This has been demonstrated in experimental trials where externally water-quenched samples showed the greatest internal stress and resulting warpage [29–31, 35]. The application of internal mold pressurization was shown to reduce warpage [34, 35].

In another study using polyethylene, it was shown that external water cooling also caused greater warpage and shrinkage compared to external air cooling. This is mainly influenced by density variations in the polymer, which are a function of degree of crystallinity. Apart from the residual quench stress, the temperature at which the polymer released from the mold wall is also a factor contributing to warpage. Higher release temperatures resulted in greater warpage [36].

A reduced internal pressure induced in the mold during the cooling process is another possible factor influencing warpage formation, in addition to the thermally induced residual stresses. In the heating stage, pressure inside the mold increases due to expansion of air, resulting in a pressure difference between the internal air and the outside atmosphere. Mass transfer of air occurs from the inside of the mold to the outside through the vent pipe. Subsequently, during cooling, there is a pressure drop inside the mold, and cold air is drawn from the outside atmosphere into the mold. Because of the wall friction of the venting pipe, mass transfer of air between the inside and outside of the mold was limited. As the external cooling rate was high, a vacuum was induced inside the mold, pulling the semimolten polymer inward to cause part warpage. However, the relative significance of residual stress and in-mold reduced pressure on warpage formation of rotational molded parts was not addressed [34].

In summary, slow cooling gives higher level of crystallinity and causes formation of larger spherulites. Nonuniform cooling induces thermal quench stresses and causes warpage. Apart from the residual quench stress, the temperature when the polymer released from the mold wall also affects warpage factor. A higher release of temperature results in greater warpage. Mold pressurization can reduce the extent of warpage.

Impact Properties

The mechanical properties of rotomolded articles, particularly the impact strength, are strongly influenced by the variation in microstructure and level of degradation of the internal layer of the part [37]. Maximum impact strength is obtained when all of the bubbles disappear and the fusion between the particles is good with no degradation on the internal layers of the part. Poor cohesion at the particle boundaries and the presence of voids due to incomplete sintering gives poor mechanical properties. The impact strength of overheated polyethylene parts is poor due to the crosslinking of the molecules at the internal layers [37, 38].

Figure 9a shows the morphology of polyethylene with no degradation. In slightly overheated polyethylene parts, there is a thin layer of imperfect spherulites at the internal surface (Fig. 9b). Next to the thin layer is a columnar-type structure consisting of bundles of parallel fibrils (Fig. 9b). As higher levels of overheating takes place, the columnar structure is preceded by a thin layer of nonspherulitic material at the free surface (Fig. 9c). In all cases, there is a transcrystalline layer at the external surface, which is in contact with the mold. There was no evidence that this reduced the impact strength [38].

Cramez et al. [39] examined the effect of cooling rates on the impact strength of a rotational molding grade of

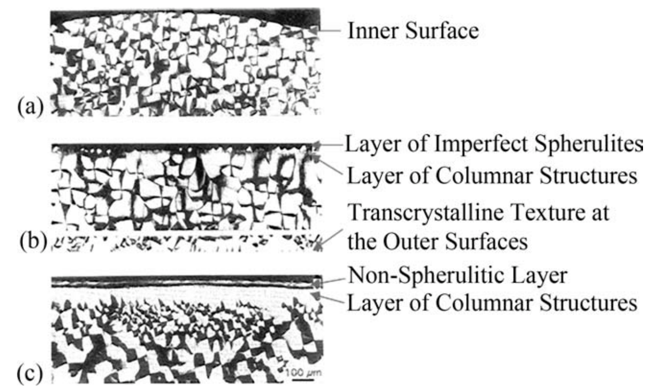

FIG. 9. Micrograph showing the morphology of polyethylene under various conditions, (a) no degradation, (b) slightly overheated, and (c) highly overheated.

polypropylene. They noticed marked improvement when high rates of external cooling were applied. However, nonuniform cooling through the part thickness caused severe warpage and uneven morphology. Small spherulites at the external surfaces grew bigger toward the internal surfaces. The authors suggested the use of high cooling rates on both external and internal surfaces of the part to improve the ductility of rotationally molded polypropylene parts.

In rotational molding of polypropylene, slow cooling produced coarse spherulitic morphology, which gave low yield stress and fracture toughness. Fast cooling gave a smaller spherulite size. Cooling rate also strongly influenced the part density and consequently the crystallinity. High cooling rate improved the ductility of the samples. The failure mode was seen to change from brittle to ductile, accompanied by improved impact resistance. This was explained by the decrease in crystallinity as fast cooling was applied. The polymer crystallized at lower temperatures and was partially hindered, resulting in lower amount of a less perfect crystalline phase. Therefore, the part had a higher amorphous (flexible) content with a higher number of interlamellar and interspherulitic tie-molecules, which improved its ductility [39].

The nature of the spherulite growth also characterizes the environmental stress-cracking behavior of linear polyethylene and its impact strength. By rapidly cooling the Ziegler-type polyethylene, the impact strength improved significantly [40]. Void-free parts with no sign of degradation in the internal layer exhibited best properties. Simultaneous reduction of spherulite size and degree of crystallinity can be obtained via fast cooling on both sides of the part to improve the impact strength and ductility [31, 41].

Pick et al. [42] examined the effect of varying cooling rates on morphology of rotationally molded metallocene catalyzed LLDPE. They showed that slow cooling again resulted in high crystallinity with formation of large spherulites which reduced the impact performance, particularly at low temperatures. The high level of crystallinity

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was associated with a shift in the β transition of the material to a higher temperature, giving a higher brittle-ductile transition.

In general, high cooling rates reduce the level of crystallinity and improve the impact strength. Cooling from only one side of the mold can give rise to shrinkage and warpage problems. Balanced cooling from both sides of the mold was, therefore, recommended [8].

CONCLUSION

To date, most rotational molding procedures cool the mold externally relying on conduction through the mold wall to cool the inner surface, thereby, solidifying the plastic. In addition to prolonging cooling times, this can also create structural variations across the mold wall leading to warpage and distortion, especially with thick wall products [43]. These drawbacks can be overcome, or minimized, if cooling is applied, both externally and internally to provide a more balanced thermal gradient across the part [44]. However, in addition to achieving more uniform cooling rates throughout the molding, and enabling significant reductions in cooling, and hence cycle time, to be achieved, internal cooling methods may also result in a deterioration in the quality of the internal surface and add to the cost, complexity, and control of the process.

For example, introduction of high velocity compressed air into the mold via air movers can produce wrinkles on the internal surface of molded parts. Also when this approach is adopted, measurement of internal temperature should be based on material rather than internal air measurements (as has often been the case), which can be misleading because the thermocouple temperature is strongly affected by the internal air supply.

Introduction of cryogenic carbon dioxide or carbon dioxide coolants into the mold have largely been unsuccessful due to the additional practical complexities involved, particularly in connecting the auxiliary arm for transfer of coolant to the rotating mold, the extra cost incurred, and the limited control over the internal cooling rate was achievable.

Water spray cooling offers several advantages for internal cooling as it is cheap, readily available, and practically, easier to implement. Water also provides greater flexibility in varying the operating parameters for optimum cooling rates, the ability to exploit phase changes occurring, in particular the latent heat of vaporization while ameliorating detrimental internal damage to the parts. Work by the authors has shown that significant reductions in cooling time are possible by this approach, particularly with optimized parameters, such as spray droplet size and velocity created with an ultrasonic spray nozzle. Laboratory and industrial trials have verified the potential of this approach in giving enhanced cooling rates, more balanced internal and external cooling and hence greater structural uniformity across moldings, combined with an acceptable internal surface quality.

As has been discussed in this review, the introduction of accelerated internal cooling measures should always be considered in association with the resulting effects on polymer morphology. In this regard, rapid and symmetrical cooling across the mold generally results in smaller spherulite size, increased mechanical properties and less potential warpage or distortion in moldings.

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