Optimisation of Multi-Layer Rotationally Moulded Foamed Structures

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Abstract. Multi-layer skin-foam and skin-foam-skin sandwich constructions are of increasing interest in the rotational moulding process for two reasons. Firstly, multi-layer constructions can improve the thermal insulation properties of a part. Secondly, foamed polyethylene sandwiched between solid polyethylene skins can increase the mechanical properties of rotationally moulded structural components, in particular increasing flexural properties and impact strength (IS). The processing of multiple layers of polyethylene and polyethylene foam presents unique challenges such as the control of chemical blowing agent decomposition temperature, and the optimisation of cooling rates to prevent destruction of the foam core; therefore, precise temperature control is paramount to success. Long cooling cycle times are associated with the creation of multi-layer foam parts due to their insulative nature; consequently, often making the costs of production prohibitive. Devices such as Rotocooler®, a rapid internal mould water spray cooling system, have been shown to have the potential to significantly decrease cooling times in rotational moulding. It is essential to monitor and control such devices to minimise the warpage associated with the rapid cooling of a moulding from only one side. The work presented here demonstrates the use of threaded thermocouples to monitor the polymer melt in multi-layer sandwich constructions, in order to analyse the cooling cycle of multi-layer foamed structures. A series of polyethylene skin-foam test mouldings were produced, and the effect of cooling medium on foam characteristics, mechanical properties, and process cycle time were investigated. Cooling cycle time reductions of 45%, 26%, and 29% were found for increasing (1%, 2%, and 3%) chemical blowing agent (CBA) amount when using internal water cooling technology from ~123°C compared with forced air cooling (FAC). Subsequently, a reduction of IS for the same skin-foam parts was found to be 1%, 4%, and 16% compared with FAC.

INTRODUCTION

Rotational moulding is a process that uses heat and biaxial rotation to manufacture hollow plastic products such as tanks, containers, and playground equipment. In conventional rotational moulding both the mould and polymer are heated from room temperature up to the melting point of the polymer, and subsequently cooled back to room temperature. This repetitive heating and cooling sequence results in long cycle times, often causing prohibitively high productions costs. In rotational moulding, it is possible to manufacture double walled or sandwich structures, known as skin-foam-skin structures, where the two skins are separated by a foam core. Sandwich structures in rotational moulding commonly make use of a chemical blowing agent (CBA); CBA's decompose at a specific temperature, generating an expanding gas which is dispersed throughout a polymer melt to develop a thermoplastic foam layer [1, 2]. The long cycle times previously mentioned are extended greatly when moulding multi-layer parts, where the mould must be removed from the oven multiple times during the heating cycle to add additional layers of polymer and CBA. Additionally, foamed components are naturally insulative, thus extending the cooling phase considerably.

Traditionally, the cooling phase in rotational moulding has been carried out externally using either forced air cooling (FAC), external water spray cooling, or external evaporative cooling (misting) [1, 2]. In these methods of external cooling, the heat must be conducted across the thickness of the polymer and through the mould, which is subsequently cooled by convection on the external surface of the mould. The cooling of a polymer has a direct effect on the mechanical properties of a rotationally moulded part, as higher cooling rates result in a lower degree of crystallinity [1, 3]. High cooling rates have also been demonstrated to result in an increase in IS [4]. Additionally, it is well reported that unsymmetrical cooling of a component is major cause of warpage associated with the temperature differentials across a thick wall [5-7]. Recent advances in rotational moulding have progressed internal mould cooling to commercial viability with devices such as Rotocooler®. Such devices use a rapid internal water spray system to quickly cool the internal space of the mould at a specific time (Fig. 1), and is thought to be the most efficient method of heat removal in order to achieve an effective reduction in cycle time [5, 8]. This technology has the potential to enable the control of heat loss gradients through the careful control of both internal and external cooling rates. The combination of internal and external water cooling has also previously been shown to result in lower average warpage when compared to external water cooling alone [5].

The objective of the work presented here is to examine the effect on physical and mechanical properties from the application of various cooling mediums on rotationally moulded skin-foam parts, and subsequently analyse the process cycle time for each. A series of polyethylene skin-foam mouldings were produced using rotationally moulded polyethylene in powder form. Threaded thermocouples were used during experimentation to monitor the polymer melt temperature in order to analyse the cooling cycle of the moulding process. After moulding, characterisation of the IS of the moulded parts was performed.

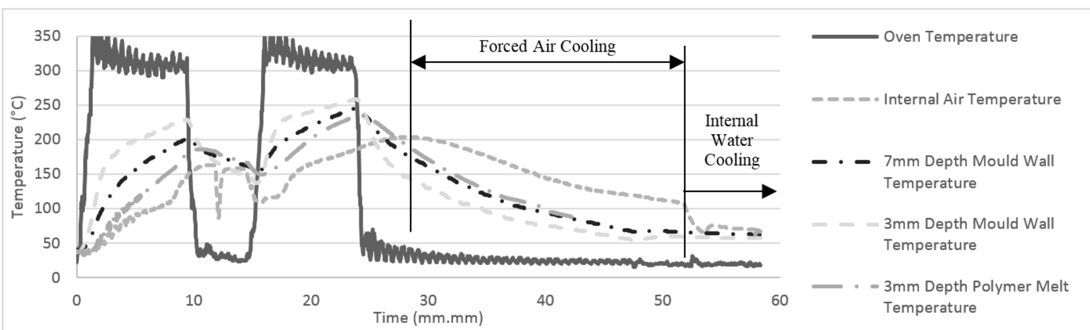


FIGURE 1. Internal Water Cooling effects on the Internal Air Temperature of a mould at 195°C for a skin-foam part when internal water spray cooling is applied at 123°C in the cooling cycle.

MATERIALS AND METHODS

Materials

Resin

Metallocene medium density polyethylene (PE) resin (mMDPE; Lumicene® M3583 UV) from Total Petrochemicals & Refining S.A./ N.V. (Brussels, Belgium) was used for conducting the work presented. The resin was supplied and used in powder form. Table 1 presents the typical properties [9].

TABLE 1. Typical Properties of Lumicene® M3583 UV [9]

Properties of the Resin Used	ISO Method	M3583 UV
Melt index (190°C/ 2.16 kg; g/10 min)	ISO 1133	6
Density (g/cm^3)	ISO 1183	0.935
Melt temperature (°C)	ISO 11357-3	123

Chemical Blowing Agent

Celogen OT from Uniroyal Chemicals (Mapleton, Illinois) was used as the CBA for preparing the multi-layer experimental samples. Table 2 presents the typical properties provided by Uniroyal Chemicals [10]. Celogen OT is reported to have a decomposition temperature between 158 and 160°C, producing 125 cm^3/ g of 91% N_2 and 9% H_20 [10]. The selected Celogen OT grade had an average particle size of 3µm. When producing foam layers, M3583 UV powders were completely dry-blended with specific amounts of Celogen OT; the mixture was then added to the mould at the required time. Premature decomposition of CBA was prevented through the use of appropriate temperature control.

TABLE 2. Typical Properties of Celogen OT [10]

Product name	Celogen OT
Chemical composition	4, 4' – Oxybis (benzenesulfonylhrazide)
Appearance	White powder
Decomposition temperature	158 - 164°C
Gas yield	125 cc/g
Gas composition	Nitrogen, steam
Specific gravity	1.55 @ 25°C
Bulk density	496 kg/m^3
Average particle size	2.4 - 3 µm

Manufacturing of Samples

The rotationally moulded parts manufactured for this work were accomplished using a Ferry Rotospeed 1600 carousel-type biaxial two arm machine. A 10mm thick aluminium cube mould measuring 200 x 200 x 200mm with a central vent hole was used. The rotational speed ratio was set to 8 r.p.m: 2 r.p.m (rotations per minute), and an oven temperature of 300°C was used. A Datapaq device was used to monitor the oven and air temperature inside the mould throughout the moulding cycle. K-type exposed thermocouples were used, and the temperature data was wirelessly transmitted to a receiver located external to the rotational moulding machine. Additional threaded thermocouples were used to analyse the mould temperature at two depths (7 mm and 3 mm to the inside face of the mould), and the melt temperature of the first skin layer. All samples were heated to a peak internal air temperature (PIAT) of 195°C before being cooled to 70°C by various mediums, followed by demoulding.

Figure 2 demonstrates the different cooling approaches applied to manufacture single layer and skin-foam parts. The thickness of skin layers was ~2.5 mm; foam layers had a shot weight of 300g total, whilst the amount of CBA was adjusted accordingly by weight percentage (wt%). Ambient cooling was achieved with the Rotospeed cooling chamber door in the open position, maintaining an 8 r.p.m: 2 r.p.m rotation speed ratio, and the cooler fan turned off. FAC was conducted with a volume of air of 8000 Cubic Feet per Minute (CFM) flowing in to the cooling chamber. For water cooled (WC) samples a Rotocooler® rapid internal mould water spray cooling system was utilised. Internal water spray cooling was applied at temperatures both above and below recrystallization (~123 & ~195°C). The system used a cone shaped pneumatic spray nozzle with a mass flow rate of 0.0376 kg/min to deliver an atomized water spray. To facilitate cooling, the mould was removed from the cooler, the spray nozzle was inserted through the mould vent tube, and the nozzle activated at the specified temperature during the cooling cycle.

Mechanical Property Testing

Impact tests were performed to samples cut from rotationally moulded parts according to ISO 6603-2:2000. Impact tests were performed using a CEAST Fractovis instrumented falling dart impact tester. A total of 20 specimens were machined from each part, and measurements conducted at room temperature and -40°C. During testing, skin-foam parts were orientated so the external skin face was impacted first to replicate service loading conditions. A speed difference of <20% was maintained during experimentation.

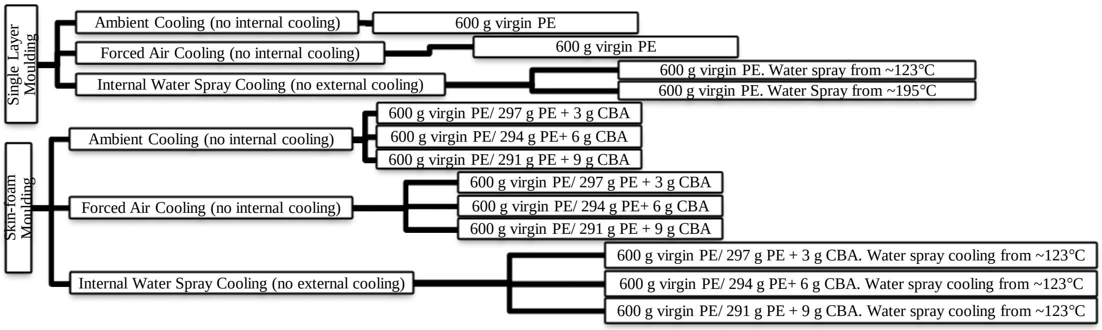


FIGURE 2. Hierarchy of mouldings presented in the current work.

RESULTS AND DISCUSSION

Cycle Time Reductions

Table 3 displays the cooling cycle times for single skin parts for various cooling mediums. The cooling cycle was calculated from the time taken to cool the parts from an initial PIAT of ~195°C to a demoulding temperature of 70°C. A cooling cycle time reduction of 33% was found for internal WC single skin parts cooled at temperatures below the M3583 UV recrystallization temperature (~123°C) when compared to FAC.

TABLE 3. Overall Cooling Cycle Times for Single Layer Parts at a PIAT of 195°C

Cooling Type	Cooler Cycle Time (hh:mm:ss)
Ambient cooling	01:06:30
Forced air cooling	00:26:00
Internal water cooling (from ~123°C)	00:17:30
Internal water cooling (from ~195°C)	00:22:04

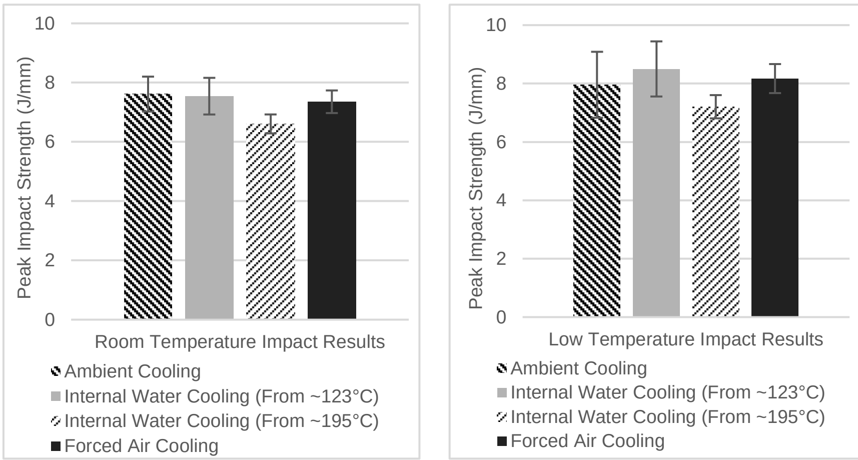
Table 4 presents the calculated cooling cycle times for skin-foam parts for various cooling mediums. Reductions of 45%, 26%, and 29% were found for skin-foam parts of increasing CBA percentage (1%, 2% and 3%) using internal WC compared with FAC. These results indicate a change in the cooling cycle time for WC skin-foam parts of variable CBA amount, and will be the subject of future investigations.

TABLE 4. Overall Cooling Cycle Times for Skin-Foam Parts at a PIAT of 195°C

Cooling Type	Percentage Chemical Blowing Agent		
	1% Cycle Time (hh:mm:ss)	2% Cycle Time (hh:mm:ss)	3% Cycle Time (hh:mm:ss)
Ambient cooling	01:13:34	01:14:12	01:09:06
Forced air cooling	00:34:52	00:32:14	00:38:38
Internal water cooling (from ~123°C)	00:19:18	00:23:46	00:27:30

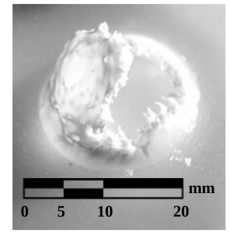
Mechanical properties of Plastic Specimens

Figure 3 shows the impact results for single layer rotationally moulded parts tested at room temperature and -40°C. It can be seen that there is no significant change in the IS of the internally WC rotationally moulded parts at either room (Fig. 3A) or -40°C temperatures (Fig. 3B). There is a decrease in IS in both room and low temperature experimentation when water cooling is initiated from elevated temperatures compared with water cooling around the recrystallization temperature of M3583 UV. Figures 4A and 4B show the ductile (4A) and brittle (4B) failure behaviour observed during room temperature and low temperature impact tests on FAC single layer parts respectively.

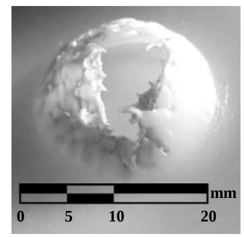


(A) (B)

FIGURE 3. IS of single-layer rotationally moulded parts at room temperature and – 40°C.



(A)



(B)

FIGURE 4. Impact behaviour of FAC single-layer parts at room temperature (A) and – 40°C (B).

Figure 5 shows the results from skin-foam impact tests on moulded parts at room temperature and -40°C. The IS reduction for WC skin-foam parts of increasing CBA amount (1%, 2%, and 3%) is 1%, 4%, and 16% respectively compared with FAC. Figures 6A and 6B show the ductile (6A) and brittle (6B) failure behaviour observed at room and low temperature impact tests on WC (~123°C) 1% CBA skin-foam parts.

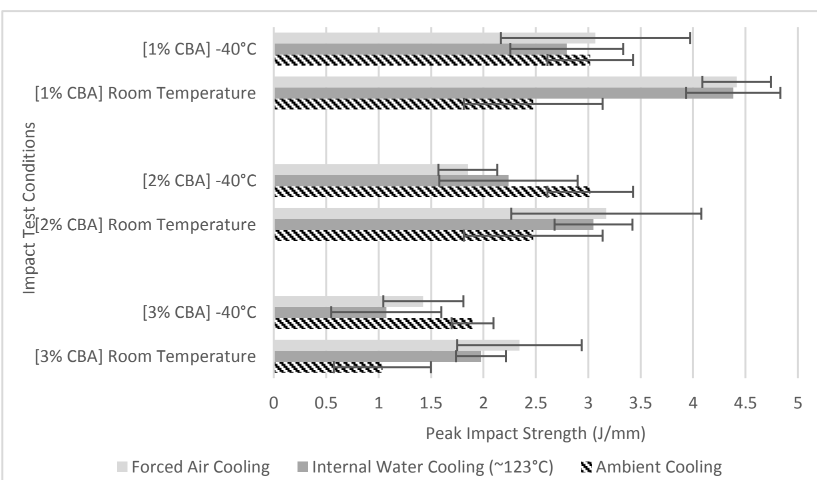
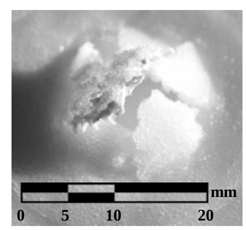
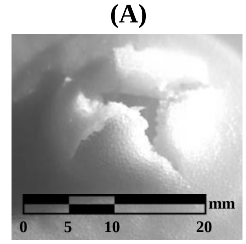


FIGURE 5. IS of skin-foam rotationally moulded parts of increasing CBA amount (1%, 2% and 3%) at room temperature and – 40°C.



(A)



(B)

FIGURE 6. Impact behaviour of WC (~123°C) 1% CBA skin-foam parts at room temperature (A) and – 40°C (B).

Part Appearance Observations

Figure 7A shows the internal face of the WC from ~195°C part, and highlights the deformation of the face opposite the water injection location due to a higher melt temperature. No deformation was observed on WC parts from ~123°C. Figure 7B and C show a cross section of foam roughness for 3% FAC (7B) and WC (7C) (~123°C) skin-foam parts. It can be observed that water cooling produced a smoother foam surface; however, water cooling also produced a part that was darker in colour than the FAC 2 and 3% CBA parts.

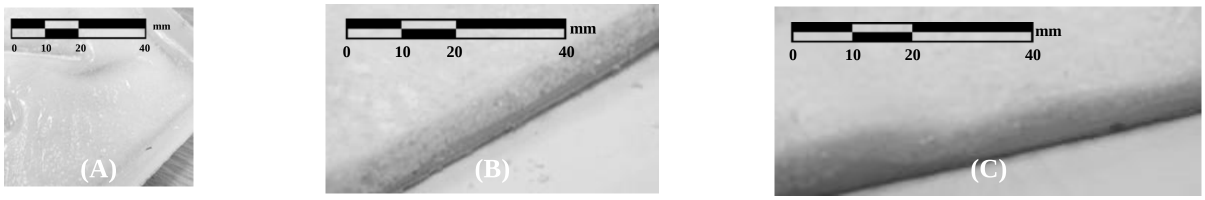


FIGURE 7. Part appearance observations after de-moulding.

CONCLUSIONS

The following conclusions are drawn based on cycle time reduction, impact results, and part appearance findings:

- A cooling cycle time reduction of 33% was found for WC single layer parts cooled at temperatures from ~123°C when compared to FAC.
- Cooling cycle time reductions of 45%, 26%, and 29% were found for increasing (1%, 2%, and 3%) CBA amount when WC from ~123°C compared with FAC.
- The reduction of IS for WC skin-foam parts of increasing CBA amount (1%, 2%, and 3%) is found to be 1%, 4%, and 16% compared with FAC.
- No significant change in the IS of rotationally moulded parts WC from ~123°C at either room or freezing temperatures was found.
- Internal water spray cooling at temperatures significantly greater than the melt temperature of M3583 UV is found to cause significantly more deformation to the internal surfaces.

The results indicate a change in cooling cycle time for WC skin-foam parts, and will be the subject of future investigations. The effect of cooling medium on skin-foam-skin impact strength, cooling cycle, and part appearance will be investigated. Changes in skin-foam/ skin-foam-skin compression and flexural strength will also be explored.

ACKNOWLEDGMENTS

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