PROCESS CONTROL FOR ROTATIONAL MOULDING OF PLASTICS

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ABSTRACT

In recent years the rotational moulding process for plastics has become more sophisticated in terms of equipment design and the complexity of the moulded products. However, a major drawback has been the lack of precise process control due to the difficulty of getting information about what is happening to the powder/melt as it coats the inside surface of the rotating mould.

To overcome this problem, a new control system has been developed whereby temperature measurements are taken from inside the mould as it rotates and these are transmitted to a computer or to the machine control system. Although the control signal can be taken from the metal mould or from the melt temperature, it has been found that measurements of the internal air temperature provide more accurate control information. For example, from this measurement it is possible to identify (i) when the powder starts to stick to the mould, (ii) when the powder has all melted, (iii) when optimum impact strength of the moulding has been achieved, and (iv) when the plastic has solidified sufficiently for demoulding.

In addition, the introduction of a modest gas pressure inside the mould at a strategic point in the cycle can improve very significantly the product quality and reduce manufacturing times.

INTRODUCTION

In its most basic form, rotational moulding is a method for producing hollow plastic articles. A predetermined charge of cold plastic powder is placed in one half of a cold mould -usually sheet steel or cast aluminium. The mould is then closed and subjected to biaxial rotation in a heated environment as shown in Fig. 1. As the metal mould becomes very hot, the plastic powder tumbling inside the mould starts to melt and coat the surface of the mould. When all the powder has melted, the mould is transferred to a cooled environment. The biaxial rotation continues until the plastic has solidified. At this point the mould is opened and the part is removed. The final product used need not be hollow since finishing operations such as cutting or sawing can be used to make, for example, right and left handed articles.[1-6]

Modern commercial rotational moulding machines can have quite sophisticated microprocessor control over the timings within the moulding cycle. However, unlike other plastic processing methods such as injection moulding or extrusion, where feedback control is based on recordings from within the melt, this has not been possible with rotational moulding due to the complex biaxial rotation of the mould. Thus, it has not been possible to have precise process control since conditions are being monitored quite remotely from the plastic melt. This problem has made it difficult to develop a fundamental understanding of what is happening to the plastic during rotational moulding.[7-11]

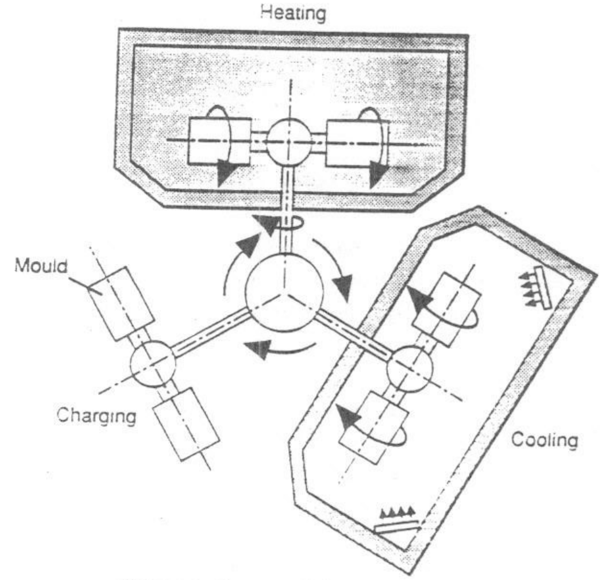

Figure 1 Carousel Type Machine

To alleviate such problems, a major programme of research was initiated about 10 years ago and it set out to provide fundamental information in a number of key areas:

(i) What is the mechanism by which the plastic powder forms a coating on the inside surface of the mould?

(ii) Can speed ratios and other processing parameters be optimised by methods other than trial and error in order to give products with a controlled wall thickness distribution and maximum values of mechanical properties?

(iii) Can an accurate control system be devised for the process?

(iv) Can products be manufactured without the internal and surface pin-holes which are so characteristic of rotationally moulded products.

(v) Can multiple shot moulding be avoided for situations where multi-layer products are required?

This paper will describe the outcome of this research and will illustrate how all the above questions can now be answered in ways which will strengthen the future development of the rotational moulding process.

TEST EQUIPMENT

The rotational moulding trials in this work were carried out using (a) a Caccia 1400 A shuttle type machine. (b) a Ferry Rotospeed carousel type rotational moulding machine with independent arms.

The moulds used in this work were 'cube' shaped, 440 x 440 mm at the top and 400 x 400 mm at the base or 330 x 330 mm at the top and 300 x 300 mm at the base. A PTFE vent tube was placed in the centre of the base. A PTFE vent tube was placed in the centre of the larger end face of the 'cube'. The mould was manufactured from 16 gauge (1.6 mm thick) sheet steel. This mould was used for simplicity of operation, but it has been confirmed from extensive trials that the results and conclusions reported here are independent of mould shape.

PROCESS CONTROL

Rotational moulding is unique among the manufacturing processes for plastics in that heating, shaping, densification and cooling all occur inside the mould. Although rotational moulding may appear to be a simple process, in fact there is a complex interaction between a large number of variables. These include:

(i) oven temperature (ii) oven residence time (iii) amount of plastic in the mould (iv) speeds of rotation of the mould (v) nature of the cooling medium (vi) duration of the cooling periods.

In addition, a number of other factors influence the quality of the product although they may not be under the direct control of the moulder. These include: (a) Powder particle size (b) Powder particle size distribution (c) Melt flow behaviour of the plastic (d) Density of the plastic (e) Mould material (f) Shape of the mould (g) Thickness of the mould (h) Efficiency and type of oven (i) Efficiency and type of cooling bay.

In the past, optimum process conditions had to be established by trial and error but modern process control methods enable these conditions to be obtained more conveniently and quickly. In particular, a system called ROTOLOG was developed by Queen's University and Exxon Chemicals and this enables direct real time process control based on the temperature of the air inside the mould. A particular advantage of this type of control is that it provides a single feedback signal on which the whole process can be controlled.

Typical Moulding Cycle

The variations of oven, mould and polymer temperature during a typical rotational moulding cycle are illustrated in Fig. 2. In this case the oven temperature has been set at 305 °C. Line W indicates the temperature rise of the air close to the outside surface of the mould. The cycle fluctuations reflect the fact that the oven is not a completely homogeneous temperature environment.

Lines X and Y in Fig. 2 show the temperature rise of the outside and inside surfaces of the mould. The differences between these two lines will depend on the mould material and the mould thickness. The greater the thickness of the mould the greater will be the spacing between the two lines. Conversely, the use of a mould material with a high thermal conductivity will cause the lines to move closer together.

Line Z in Fig. 2 shows the temperature rise of the air inside the mould. This line is the basis of modern control system for rotational moulding because it highlights all the significant events happening inside the mould ie powder adherence to the mould, melting of the powdered plastics, densification of the sintermelt, the maximum temperature experienced by the inner surface of the product and the crystallisation/solidification of the melt.

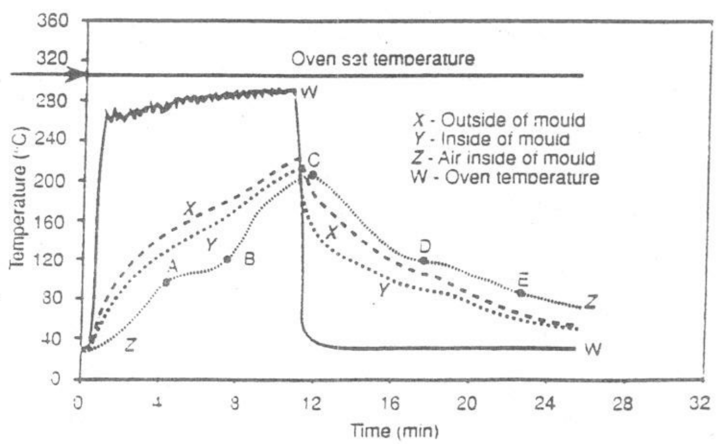

Figure 2 Typical rotational moulding cycle

The period up to point A is usually referred to as the **Induction Time**. It is the period during which the powder is tumbling freely inside the mould and is being heated but there is no adherence to the mould because the temperature is too low. Between A and B the powder is melting and building up the thickness of the product on the inside surface of the mould. During this period the majority of the heat being input to the system is being absorbed by the melting process and so the temperature of the internal air rises more slowly between points A and B. B.

By the time point B is reached, all the powder is loosely bonded to the inside surface of the mould to form the sinter-melt. By the time point B is reached, when the melting process is completed, the temperature of the air inside the mould starts to rise more quickly again. During the period B-C, the sinter-melt starts to consolidate and slowly the trapped bubbles in the melt are diffusing/dissolving away. This phase is often referred to as the **Fusion Time**. The extent of this fusion period is not precisely defined because the disappearance of the bubbles is a time-temperature phenomenon which will extend into the section C-D of line Z ie after the commencement of the cooling stage.

Point C is crucial to product quality because although the plastic in contact with the mould will be at a higher temperature, degradation of the plastic will occur firs at the free inner surface due to the combination of temperature and oxygen present there. It is important to note also that the peak inner surface temperature (point C) occurs several minutes after the commencement of the cooling period. The extent of this overshoot will depend on the amount of plastic in the mould. If the thickness of the moulded product is small then there will be very little overshoot and the internal air temperature will start to drop almost immediately on removal of themould from the oven. However, if the moulded product is very thick, then the thermal momentum of the melt will cause the temperature of the inner air to continue to rise by 10-15°C after the mould cooling period has started.

At point D, the inflexion in line Z signifies the energy release associated with the solidification process and so the internal air cools less quickly during this stage. Between C and D the structure of the plastic is being formed and so the rate of cooling is critical during this period. If warpage/distortion is to be avoided then it is desirable that the inner and outer surfaces of the plastics should be cooled at approximately the same rate. At point D, the product is solid and so the cooling rate is less critical to the quality of the product. Hence, much faster cooling rates could be applied to reduce the cycle time which ends at point E. If a different amount of plastic powder is placed in the mould, then the line Z will change its shape since the new charge of powder will take a longer or shorter time to melt and consolidate on the inside of the mould. Fig. 3 illustrates the changes in the ROTOLOG trace for internal air temperature when

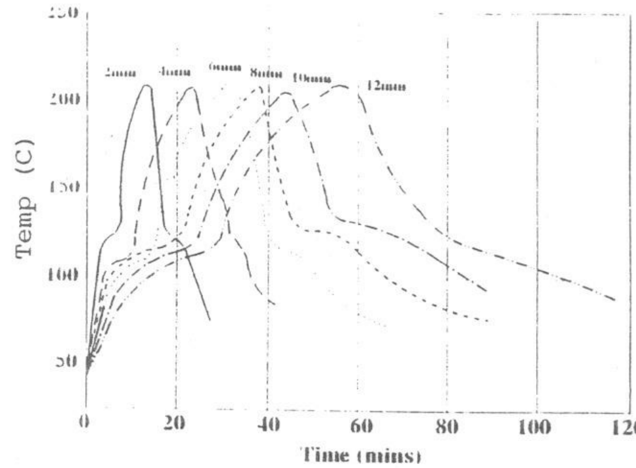

Fig. 3 Effect of product thickness on rotolog trace

different wall thickness articles are moulded. Note that in each case the control condition is that the temperature of the inside surface of the moulding always reaches the same value. This will ensure that the plastic product will have optimum mechanical properties.

PROCESS-PROPERTY INTERRELATIONSHIPS

On most rotational moulding machines the two main variables available to the machine operator are oven temperature and oven time. Fig. 4 illustrates the effects which these variables have on the impact strength of the moulded product. Of particular note is the fact that for many rotomoulded plastics, the peak mechanical performance is only available at quite specific process conditions. Fig. 5 shows the processing window which is available when both oven time and oven temperature are related to one another. In general, products moulded using any combination of oven time and oven temperature within the shaded are will be acceptable. Outside the shaded area, the combination of time and temperature will either "overcook" or "undercook" the moulding. The former condition is characterised by a shiny inner surface,possibly discoloured and with a pungent smell from the inside the product. The latter condition is characterised by an inner surface which exhibits a powdery or an "orange peel" appearance. There will also be an excessive amount of bubbles or pin-holes within the walls of the product.

It may be seen in Fig. 5 that within the moulding window there is a line which identifies the unique combinations of oven time and oven temperature to give optimum product properties. In the past the optimum would have been sought by the trial and error. However, nowadays real time measurement of air temperature inside

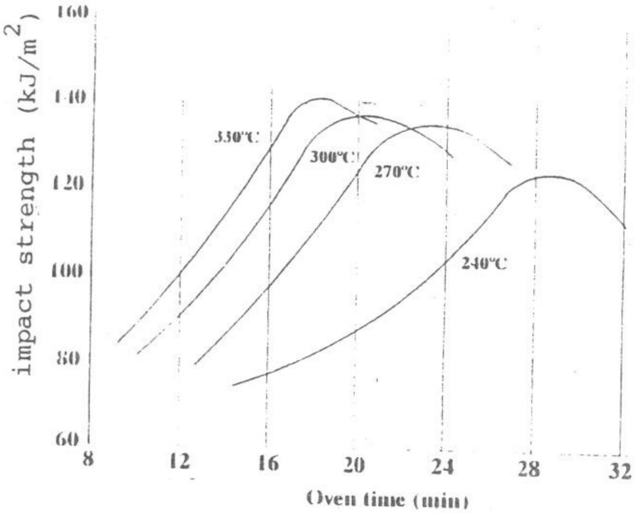

Fig. 4 Effect of oven time on impact strength

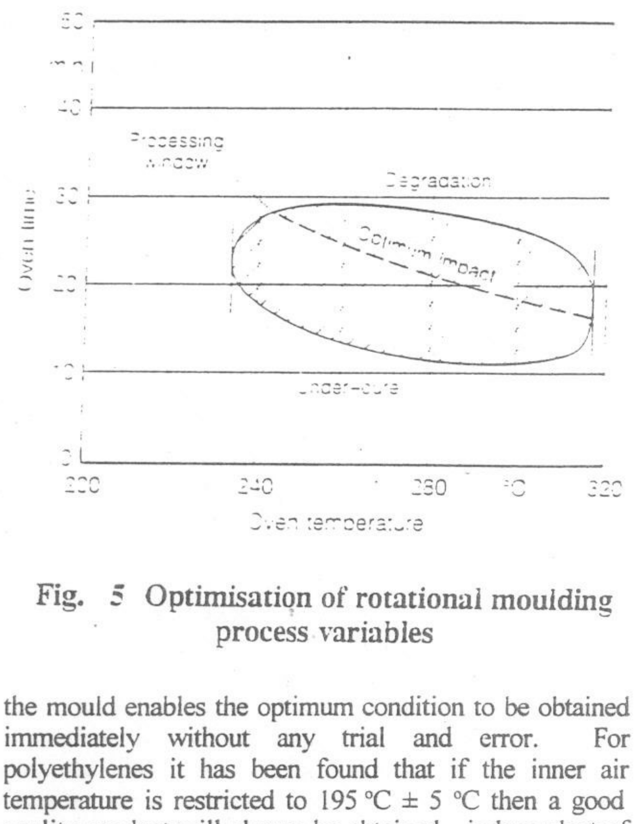

Fig. 5 Optimisation of rotational moulding process variables

the mould enables the optimum condition to be obtained immediately without any trial and error. For polyethylenes it has been found that if the inner air temperature is restricted to 195 °C ± 5 °C then a good quality product will always be obtained - independent of all other machine variables.

PIN HOLES IN ROTATIONALLY MOULDED PRODUCTS

During rotational moulding of plastic powders or liquids it is almost inevitable that bubbles will form at the interface between the plastic and the mould and within the wall thickness of the product. In the case of powdered plastics, the bubbles occur because the powder particles melt at their surface and fuse together in a manner that traps an irregularly shaped pocket of gas. As time progresses, the pocket of gas transforms into a spherical bubble. In the case of liquid plastics, the bubbles form due to the rotation of the mould causing turbulence in the liquid. This causes pockets of gas to get trapped in the plastisol. Originally it was thought that the temperature gradient from the hot mould to the cooler inner surface caused the bubbles to be driven out of the melt towards the free surface. This was supported by the fact that when a cooled moulding was sectioned, there was a greater density of bubbles at the inner surface.

However, recent research 9 using video cameras has shown that the bubbles do not move within the melt. They remain at the location where they form because the plastic melt is too viscous to permit them to move. As time progresses and the temperature of the melt increases, the bubbles get smaller and smaller until they eventually disappear. The reason why a greater density of bubbles may be observed at the inner surface of an undercooked moulding is because the bubbles in this region formed last and have had less time to diffuse into the melt. Additionally the temperature of the melt close to the inner surface is cooler than other parts of the melt nearer the mould surface.

The formation of the bubbles in powdered plastics is now known to be related to factors such as (a) powder particle size distribution (b) powder particle shape (c) mould material (d) melt viscosity.

Since the cycle is dictated by the fact that the mould must remain in the oven until the structure of the plastic has become properly consolidated, there has been considerable interest in developing ways of making the bubbles/pin-holes disappear more quickly. To this end it has been shown that additives can be included in the plastic powder which will increase the rate of bubble disappearance. Even more effective is the precise control of the environment inside the mould. Using these techniques it has been shown that cycle times can be reduced by 15-20% and properties such as impact strength can be increased by a similar amount because the plastic no longer needs to remain in the oven until the inner air temperature reaches 200 °C. If the bubbles disappear more quickly then the product can be taken out of the oven at an internal air temperature of, say, 175 °C. This has the double benefit of lower cycle time and less thermal degradation.

The most important finding from recent research (12) in this area is that the introduction of a low pressure (typically 0.5 Bar) for a short period of time will cause the bubbles and pin-holes to disappear. It is very important that this pressure is not introduced into the mould when the bubbles are being formed ie region OAB in Fig. 2. If this occurs then no beneficial effect is obtained because there is no pressure differential inside and outside the bubble. However, if once the bubble is formed (after point B, Fig. 2) a pressure is introduced inside the mould, then the bubbles disappear very rapidly- both within the wall thickness of the moulding and at the surface in contact with the metal mould.

Extensive trials have shown that the optimum time to introduce the pressure is when the air temperature inside the mould is about 30 °C below its normal peak value. The bubbles then disappear and the mould can be removed from the oven. It should be noted that a similar effect can be achieved by introducing a vacuum to the mould during the period when the bubbles are forming (OAB, Fig. 2) and releasing this once the bubbles have formed (region BC, Fig. 2).

CONCLUSIONS

A system has been developed which permits real time control of the rotational moulding process by permitting measurements to be taken from inside the mould while it is rotating inside the oven. This enables the moulder to:

(i) Obtain the correct moulding cycle for new moulds/new materials first time; (ii) Minimise ccletimes; (iii) Monitor quality control; (iv) Trouble shoot; (v) Control cooling cycle; (vi) Prevent degradation of material properties; (vii) Maximise part performance; (viii) Research and develop new materials; (ix) Establish oven and cooling efficiencies.

In addition, the characteristics pin-holes and bubbles in rotomoulded products can be completely removed at will by introducing pressure or vacuum to the mould at strategic points in the cycle. This improves product quality and reduces cycle time.

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