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Mould pressure control in rotational moulding

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Abstract: The technology of the rotational moulding of plastics has improved dramatically in recent years due to the recognition that measuring the temperature inside the mould is fundamental to process control. The next major advance will be made when the benefits of controlling the pressure inside the mould are fully utilized. A drawback of the rotational moulding process has always been the surface pinholes and internal bubbles that occur in the moulded part. These occur because, as the powder particles melt and coalesce, they trap pockets of air and it takes a considerable time for these to disappear.

It is known that factors such as the viscosity of the polymer melt, the shape of the powder particles, the particle size and size distribution, the mould release agent and the metal used for the mould all affect the pinholing problem. However, the major factor that influences pinhole removal is mould pressure. If pressure is applied at a strategic point in the heating cycle, it can force trapped air out of the melted plastic. Indeed the use of mould pressurization can offer additional benefits such as cycle time reduction and significant improvements in the mechanical properties of the moulded part. However, few moulders make any attempt to monitor or control the mould pressure, mainly because its effect is not understood.

This paper explains why mould pressure control throughout the moulding cycle is crucial to the rotational moulding industry in terms of, firstly, achieving good part quality and, secondly, reducing cycle times. It is also suggested that a fundamental change from passive venting to active venting of the mould is an important development that must occur in this industry.

Keywords: mould pressure control, notational moulding, plastics

1 INTRODUCTION

Rotational moulding is a manufacturing method for the production of one-piece hollow plastic parts [**1**–**4**]. It involves the placement of powdered (or liquid) plastic in a mould that is rotated in an oven, and then in a cooler, so that the plastic takes up the shape of the inside of the mould. Typical products include storage tanks, kayaks and traffic barriers. The process is characterized as being an economic means of manufacturing stress-free hollow shapes and as such it enjoys the fastest growth rate of all processing methods for plastics [**5**–**11**].

A drawback of the rotational moulding process is the surface pinholes and internal bubbles that occur in the moulded part [**1**, **2**, **12**–**16**]. It is generally agreed that part quality is best when all the bubbles have been removed from the material [**17**]. Hence, there has been considerable research interest in how the bubbles form and the mechanism by which they can be removed [**12**, **15**, **16**, **18**–**21**]. Throne and co-workers [**13**, **16**] related the concentration of pores on the surface of the moulded part to the nature of the particles, suggesting that the most desirable particle shape is cubic with rounded corners. Ramazzotti [**4**] pointed out that larger particles sizes, when used with a high-viscosity material, result in poor surface reproduction and a tendency to form bubbles in the moulded part.

Moisture content has also been identified as a cause of bubbles and pores in moulded parts. The grinding of the resin greatly increases the surface area that is available for moisture pick-up. The moisture can vaporize during moulding and create bubbles and surface pitting of the part. The addition of carbon black pigmentation can also increase the rate at which moisture is picked up.

Spence [**12**] and Kontopoulou and co-workers [**18**, **19**, **22**, **23**] have shown that a large number of parameters affect the formation and/or removal of bubbles in

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rotomoulded products. These include:

(a) powder (particle shape, size and distribution);
(b) viscosity and elasticity of the melt;
(c) additives (e.g. pigments);
(d) mould surface finish;
(e) temperature of the plastic;
(f) time of heating;
(g) atmosphere inside the mould;
(h) surface tension of plastic melt and mould;
(i) vacuum inside the mould;
(j) pressure inside the mould.

In an effort to understand the mechanism of bubble removal from rotomoulded plastic parts, Rao and Throne [**13**] drew on the theories of metal sintering and glass densification. A model was proposed to explain surface porosity, and why the buoyancy, capillary and hydrodynamic forces are not strong enough to overcome the surface tension force needed to drive the voids out of the melt. Kelly [**24**] confirmed that the high viscosity of the melt prevents movement of the bubbles.

Gogos [**15**], Kontopoulou *et al.* [**19**, **23**] and Progelhof *et al.* [**16**] have quantified the parameters that affect bubble removal and showed that migration has a very minor effect. Epstein and Plesset [**25**] showed that the terminal velocity of a bubble is given by

$$V = \frac{2}{3}\frac{\rho}{\mu}R^2 \tag{1}$$

where ρ is the density of the melt, μ is the viscosity of the melt and R is the bubble radius.

Gogos [**15**] showed that in rotomoulding, for typical density value such as 750 kg/m^3 and a typical viscosity such as 5 kPa s, a bubble of 400 μm diameter would have a velocity of 1.2 μm/min. This is so slow as to be insignificant and is consistent with the findings of Kelly [**24**].

It has also been proposed that dissolution and diffusion mechanisms play a part in bubble removal. Kelly [**24**] proposed that, at a high enough melt temperature, the air in the bubbles begins to dissolve into the polymer. Oxygen has about twice the solubility of nitrogen in polyethylene. At high temperatures, the oxygen is also depleted by direct oxidation reactions with polyethylene. The depletion of oxygen reduces the bubble diameter, which increases the pressure inside the bubble. This increase in pressure forces the oxygen and nitrogen to dissolve in the polymer; thus the bubble diameter is further reduced and this chain of events repeats until the bubble disappears. Kelly also referred to a critical bubble size above which the gases in the bubble will not dissolve, regardless of temperature or time, because the surface tension forces cannot generate enough bubble pressure to help to dissolve the gases inside the bubble.

A bubble can only exist in a liquid and remain stable if the pressure of the gas in the bubble is greater than the pressure in the melt. The pressure differential is a function of the surface tension of the melt and the radius of the bubble:

$$\Delta P = P_{\text{int}} - P_{\text{ext}} = \frac{2\sigma}{R} \tag{2}$$

where σ is the surface tension.

For the bubble of 400 μm diameter referred to above, with a typical surface tension in polyethylene of 30 dyn/cm, the equilibrium difference pressure is 300 Pa; i.e. the pressure inside the bubble must be 1.003 atm for it to remain stable. Of course, this equation is for a static situation. In rotomoulding, the conditions are changing continuously with time.

Now the extent to which the gas in the bubble can dissolve into the polymer melt is considered. This can be estimated from Henry's law, which quantifies the solubility of a gas in a liquid. It has the form

$$S = HP \tag{3}$$

where S is the solubility, P is the pressure and H is Henry's constant.

Throne [**26**] has shown that, on the basis of this equation, the amount of air that is dissolved into the bulk of the melt is relatively small. However, there will be a concentration of air in the melt at the interface with the bubble (Fig. 1). This could be a major factor in driving the diffusion mechanism by which the gas disappears through the melt. The concentration gradient will cause diffusion of the air into the melt. This causes the bubble to decrease in size, which in turn increases the pressure in the bubble. This will increase the concentration gradient by causing more air to be dissolved into the melt at the bubble interface. This results in further diffusion so that the bubble decreases in size until it disappears.

This explains why bubbles disappear from the melt, but the processes described above take time, depending on many factors and, in particular, on the initial size of the bubble. Spence [**12**] identified the factors that affect the initial size of the bubble, e.g. the nature of the powder which involves factors such as the particle size, particle shape and particle size distribution.

Crawford and Scott [**21**] carried out hot-plate tests on powders, using video equipment to record and examine the processes of melting and bubble removal in detail. The video recordings allowed the formation and subsequent dissolution of bubbles to be recorded and modelled. They showed that the initial size of the bubble has a significant effect on the rate at which it dissolves, as the surface area-to-volume ratio is inversely proportional to the diameter. They provided an empirical model for the rate of decrease in bubble size. This was later updated by Spence and Crawford [**27**–**31**] and Xu and co-workers [**32**–**34**]. An important observation in this work was the major effect of pressure.

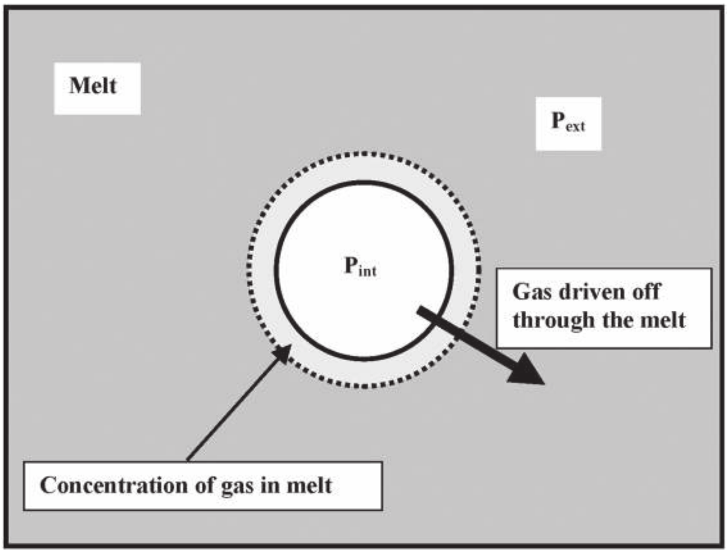

Fig. 1 Mechanism by which bubbles disappear from the melt

2 EFFECT OF PRESSURE INSIDE THE MOULD

In recent times, extensive investigations of the sintering mechanism [**19**, **23**, **35**, **36**] and analysis of bubble dynamics [**15**] have added further insight into the phenomenon of pinholes in rotomoulded parts. What is now widely recognized, particularly through the work of Spence [**12**] and more recently from the experimental results provided by Walls and co-workers [**37**], Xu [**32**–**34**] and O'Neill [**38**], is that pressure inside the mould during the heating and cooling stages of the process can have a dramatic effect on cycle time and part quality.

In theory there should be no pressure inside a rotational mould during the moulding cycle. A vent tube through the mould is intended to connect the inside of the moulded part to the external atmosphere to provide a free flow of air in and out of the mould [**39**–**41**]. This should keep the pressure inside the mould at atmospheric pressure. In practice the vent often does not work effectively and so the pressure inside the mould can vary quite considerably, above or below atmospheric pressure.

In terms of the mechanisms described earlier, the main effect of hydrostatic pressure on the melt is to reduce the diameter of the bubble. This increases the pressure in the bubble above that caused naturally by depletion of the oxygen and nitrogen. Therefore the concentration gradient around the bubble is increased, which accelerates the rate of diffusion. As shown above, the pressure differentials involved in creating the concentration gradient and driving the diffusion process are very small. Hence a relatively small hydrostatic pressure (e.g. 0.1 atm) can have a dramatic effect in making the bubbles disappear rapidly.

In order to use pressure as a process control parameter it is crucially important that both the level of the pressure and the time at which it is applied are carefully controlled. To remove pinholes, the pressure inside the mould should be slightly above the pressure inside the pinhole, and it should be applied once all the plastic has laid up against the mould and formed a fairly uniform melt (containing the pockets of gas).

Of course, most moulders are reluctant to put pressure inside the mould due to fears about safety. Such fears are fully justified because the forces generated can be very significant in a large shell-like mould. However, what most moulders do not realize is that there is already pressure generated inside the mould due to inadequate venting. The problems that they have experienced, or anticipate, are really because the levels of the existing pressures are unknown and it is the application of additional pressure that leads to the problems. If the pressure can be accurately monitored and controlled throughout the cycle, then major benefits can be derived in terms of faster cycle times and better part quality.

3 BENEFITS OF MOULD PRESSURE CONTROL

The benefits of the strategic application of pressure inside the mould during rotational moulding are twofold. These have been demonstrated through extensive tests, on a wide range of plastics, over the past decade. Firstly, the cycle time can be reduced because it is no longer necessary to wait for the natural process of gas depletion to cause the bubble removal. The main benefit is that a lower peak internal air temperature (PIAT) and thus a shorter oven time are necessary (Fig. 2). Typical reductions in cycle time are in the region of 15–25 per cent, which is very significant in a moulding method that is often criticized for its long cycle times [**2**].

The second major benefit of applying pressure inside the mould is in terms of part properties, and there are two effects here. Since the plastic does not need to be

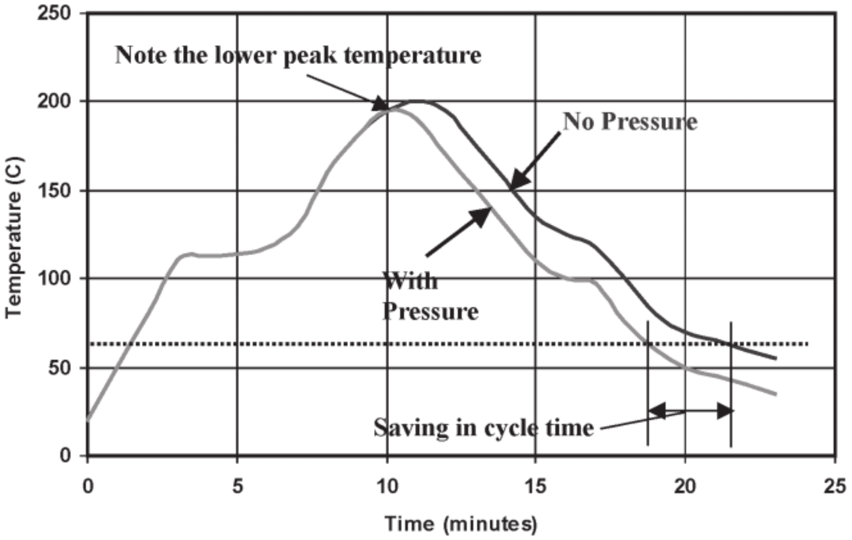

Fig. 2 Rotolog traces of polyethylene mouldings with and without pressure

heated for so long, properties such as impact strength are improved significantly. As can be seen from Fig. 2, if the thermal damage to the polymer is a function of the temperature–time experience that it has during rotational moulding, then the shorter cycle results in about 20 per cent less degradation [**42**–**46**]. Extensive trials over many years have shown consistently that the impact properties of parts produced using internal pressure are up to 20 per cent better than those produced using a normal cycle [**2**].

The use of internal pressure can also provide a benefit in terms of more consistent part quality. Normally in rotomoulding the plastic part pulls away from the mould wall during the cooling stage, due to the shrinkage. Unfortunately the point at which the plastic part separates from the mould wall occurs randomly. Sometimes it occurs in the early stages of cooling, whereas on other occasions it occurs late in the cycle.

The problem is that, once the plastic separates from the mould, the control of the cooling rate of the plastic is lost. The shrinkage and the mechanical properties depend on the cooling rate and so may be inconsistent if the release point is variable.

Internal mould pressure control can overcome this problem. A slight positive pressure is applied during the heating stage to remove bubbles and maintained until a pre-set temperature is reached in the cooler. This will keep the plastic against the mould wall in a controlled manner, which results in better quality of the moulded part and more consistent properties. In both the heating and the cooling stages, the internal pressure does not need to be very high; typically 0.1 atm (in the region of 1.5 lbf/in^2 or 10 kPa) is perfectly adequate to produce the desired results.

4 RESULTS AND DISCUSSION

There is extensive evidence to show that the application of pressure, after all the plastic powder has formed against the mould wall, improves the appearance, properties and dimensions of the moulded parts. Mouldings produced in this way are almost void free at the surface in contact with the mould, as shown in Fig. 3. Figure 4 shows the effect of pressure (50 kPa applied at about 120 °C) on the bubbles within the wall of the moulded

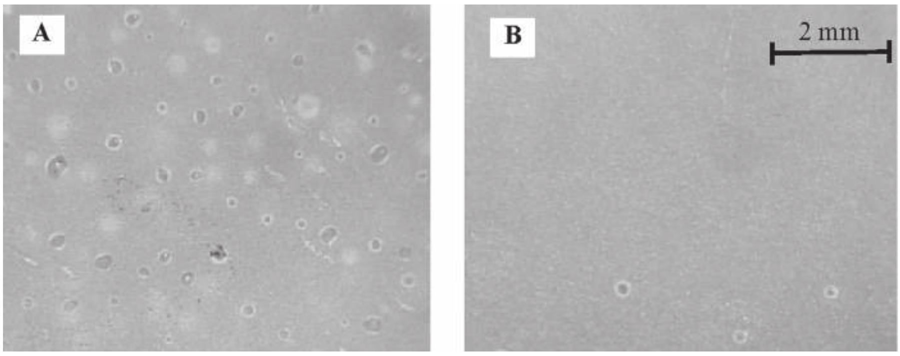

Fig. 3 Appearance of moulded surface for polyethylene parts without and with the application of pressure: A, no pressure, PIAT of 193 °C; B, pressure, PIAT of 177 °C (Borealis grade ME 8152)

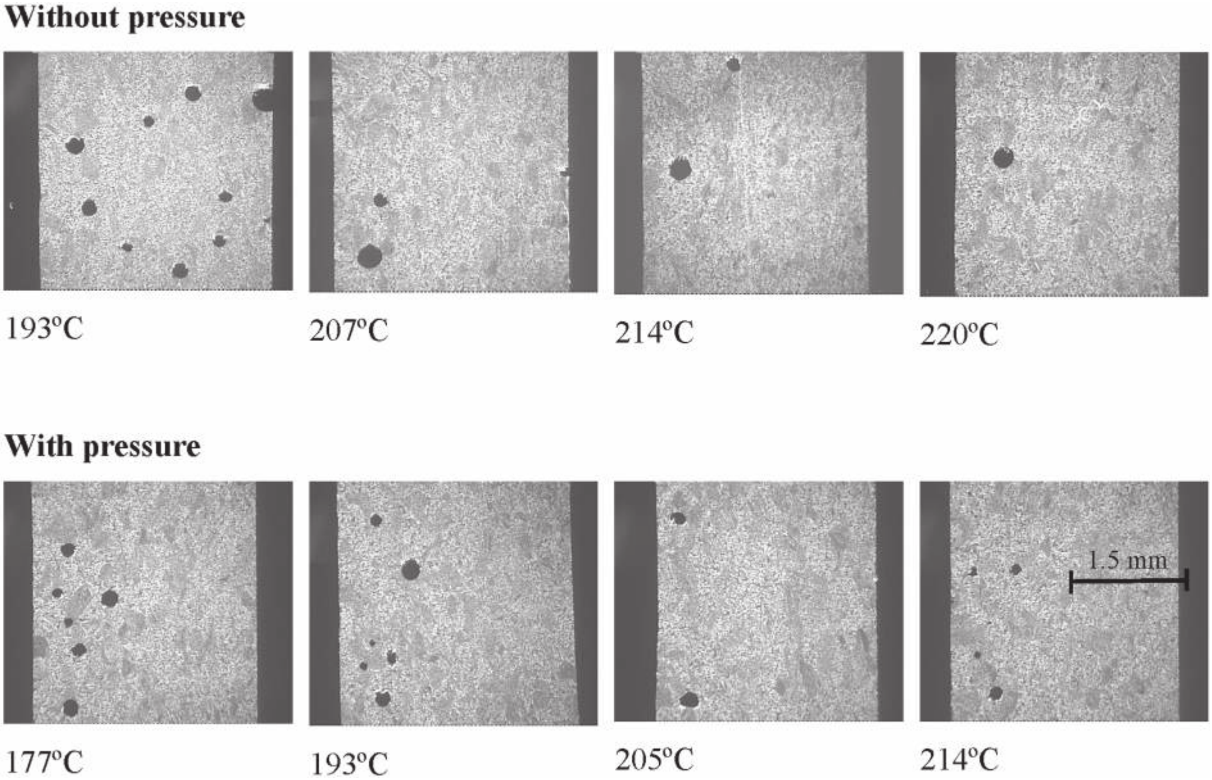

Fig. 4 Effect of the PIAT and application of pressure on the number of voids in rotationally moulded polyethylene. The mould surface is on the right of the photographs

part. These effects have been demonstrated repeatedly in the laboratory, and also by moulders around the world who have tried this technology.

Figure 5 shows the typical differences in the mould internal air temperature for parts produced with and without internal pressure. In each case, approximately the same PIAT has been used and it is evident that there is still a reduction in cycle time. This is because there is a marked increase in the cooling rate, from about 11 to 18 °C/min, when the pressurized air is introduced at room temperature. Thus, the application of pressure not only affected the diffusion of the air bubbles but also acted as a way of cooling the inside of the part. The benefit gained in terms of impact strength is illustrated in Fig. 6. The test method was an instrumented falling weight test, using a 120 mm square plaque. The test temperature was 20 °C, and similar benefits of internal pressure are obtained in low-temperature tests.

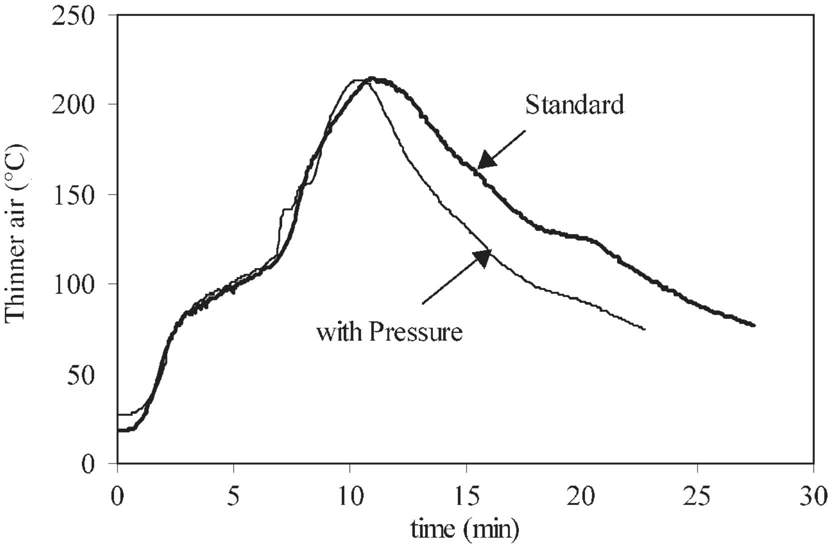

Fig. 5 Rotolog traces of polyethylene mouldings with and without pressure

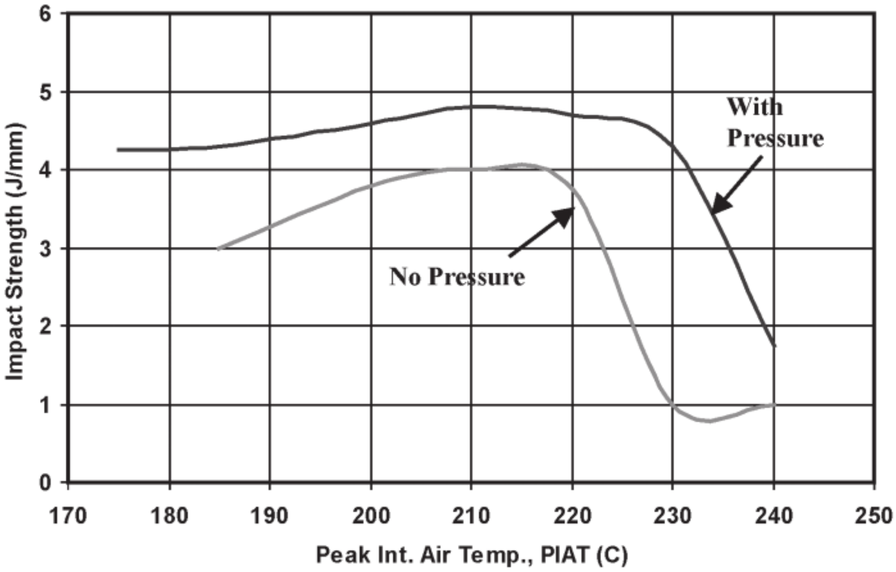

Fig. 6 Effect of internal pressure in the impact strength of polyethylene mouldings

As indicated earlier, this could be improved still further because a lower PIAT could have been used with the pressurized mouldings.

The results in Figs 5 and 6 are single examples of the effects that have been demonstrated in hundreds of moulding trials on a wide range of plastics. The experimental evidence of the benefits of controlling the pressure inside the mould is incontrovertible.

5 PRACTICAL APPROACH TO MOULD PRESSURIZATION

It is evident from the earlier discussion that it is highly desirable to monitor and control the pressure inside the mould throughout the rotational moulding cycle. The key question is: how can this be achieved in a rotating mould? It is difficult to be specific about this because there are so many different types of rotational moulding machine. On a rock-and-roll or rocking-oven machine [**1**, **2**] it is relatively easy to measure the mould temperature, the temperature of the air inside the mould and the pressure throughout the cycle. Figure 7 illustrates one convenient way to obtain continuous feedback on both temperatures and pressures throughout the cycle. In the more commonly used biaxial rotational moulding machines, more engineering ingenuity is needed to take temperature and pressure readings through two sets of rotating joints.

6 RESULTS OF TEMPERATURE AND PRESSURE MEASUREMENTS

If there is no vent, or if the vent is closed throughout the rotomoulding cycle, then the pressure variation should follow the temperature variation, since

$$\frac{P1}{T1} = \frac{P2}{T2}$$

$$P2 = P1\frac{T2}{T1} \tag{4}$$

where the temperature T is in kelvins.

In a rotational moulding cycle in which the mould is completely sealed (with no vent) data would be expected such as those shown in Fig. 8, because the pressure is directly proportional to the temperature.

If the mould is fully vented, and the vent is operating correctly, then the pressure inside the mould is atmospheric throughout the cycle. A horizontal line at zero pressure in Fig. 8 would represent this. In practice, if the pressure is monitored throughout the moulding cycle, then the pressure will usually be somewhere between these two extremes.

Consider a situation in which the vent is closed, blocked or not operating effectively. Typically the mould pressure is as shown in Fig. 9. In the early part of the cycle, no matter what state the vent is in, it is common for the air to escape at the parting line of the mould. Hence, in Fig. 9 it is seen that there is no pressure build-up for the first 5 min. Then the plastic starts to melt and seals over the parting line so that the pressure starts to build up according to equation (4). The pressure trace follows the predicted shape, and note what happens after about 17 min. At point V the internal pressure starts to become negative because there is no mechanism by which the air expelled through the parting line can get back into the moulded part. This is a common problem in rotational moulding and can lead to warping (sucking in) of the moulded part. Warping was observed in the moulded part monitored in Fig. 9.

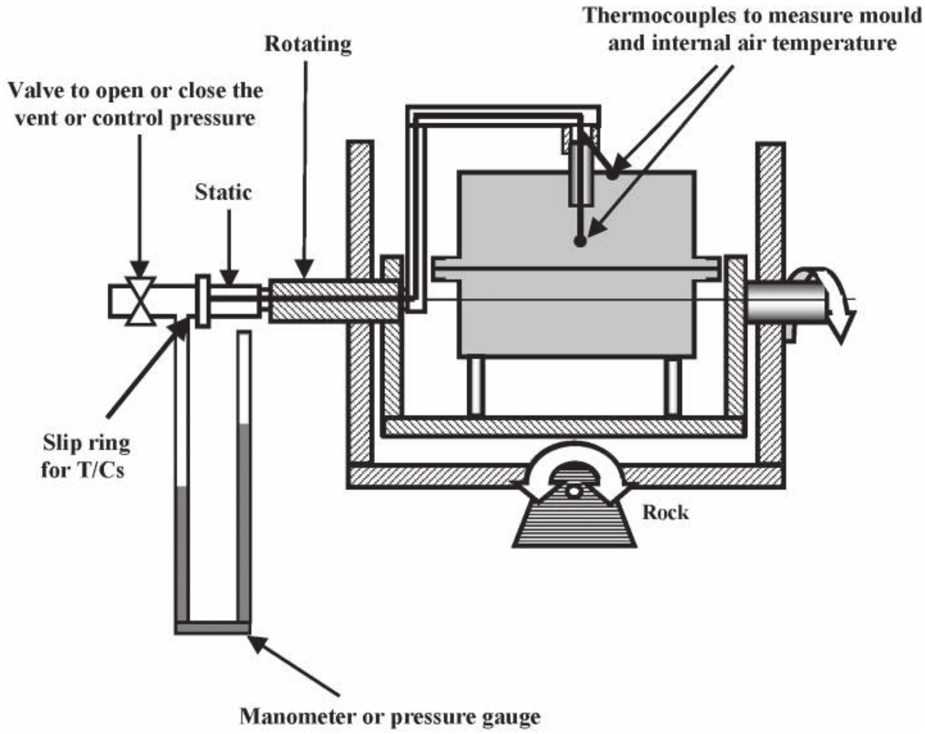

Fig. 7 Pressure and temperature monitoring system on a rock-and-roll machine (T/Cs, thermocouples)

Figure 10 is typical of another common occurrence in rotomoulding, and one that is not well understood. The venting is intended to be of good quality and operating correctly. Initially the pressure trace is similar to that in Fig. 9. There is no initial pressure build-up due to the escape of air through the vent and/or the mould parting line. Then the pressure increases as the parting line (and vent) becomes sealed with the molten plastic. However, at point L there is a sudden loss of pressure, caused by the formation of a blowhole at the parting line. This then reseals and the pressure builds up once more. From the viewpoint of quality control, this type of pressure trace is a warning that there is a potentially serious weakness (a blowhole) hidden in the wall of the moulded part. When this moulded part was inspected, it was found that there was a blowhole within the wall of the moulding, as suggested by Fig. 10.

Another interesting fact about this pressure trace is that at point M the pressure stops decreasing and starts to tend back towards atmospheric pressure. This

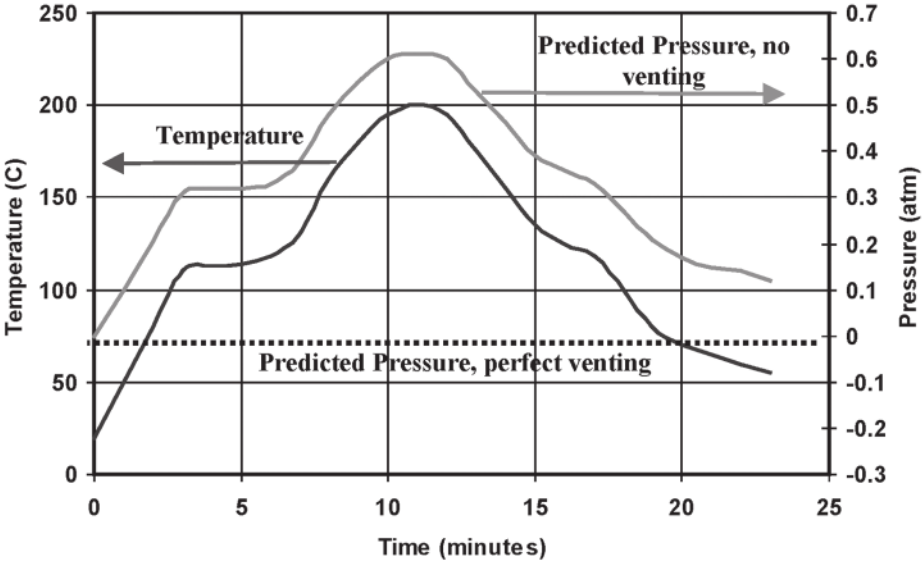

Fig. 8 Measured internal air temperature and predicted internal mould pressure

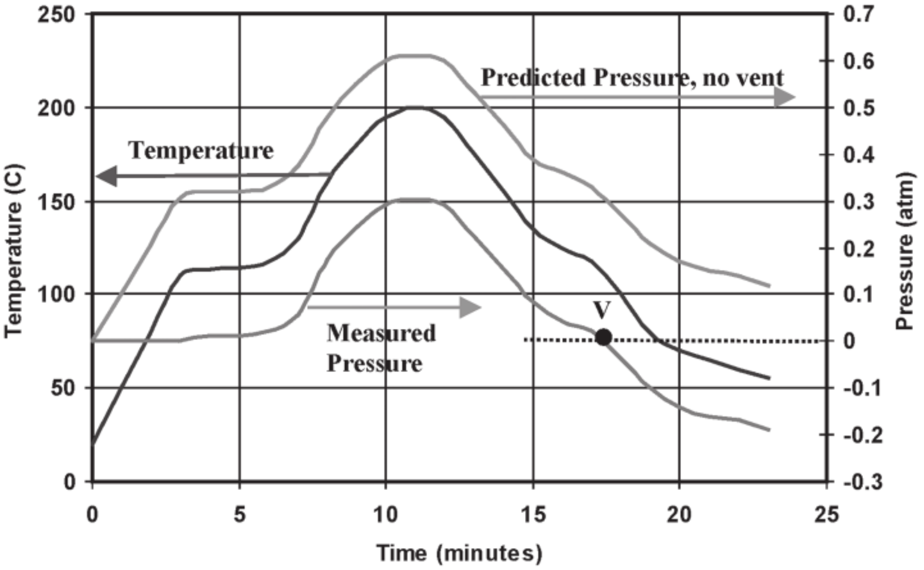

Fig. 9 Measured mould pressure for a warped part

occurs because the plastic part has separated from the mould wall (perhaps it has been pulled off by the negative internal pressure?). The pressure inside the part increases (becomes less negative) due to the reduced volume of the moulded part.

Figure 11 shows an example of the formation of a catastrophic blowhole in the part. The pressure was building up as before but this time, at point P, a blowhole formed in the part. This was too large to become resealed by the powder/melt and so it provided a continuous venting access from the inside of the moulding to the parting line. Hence, the internal pressure dropped off to atmospheric and stayed there for the remainder of the cycle.

The temperature and pressure measurements that have been discussed in Figs 8 to 11 come from measured data on a rotational moulding machine. They are only a small sample of the valuable information that can be obtained by monitoring the conditions inside the moulded part throughout the cycle.

This leads to the concept of active venting in rotomoulding [**47**]. Currently the venting is passive, in that a vent pipe is provided and any pressure generated inside the mould pushes air out of the mould to reduce the pressure. An important step forward in achieving the benefits referred to above would be the introduction of active venting, which creates the desired conditions inside the mould. This could be achieved as illustrated in Fig. 7. Instead of having a simple tube that is open to the atmosphere, a pipe to the interior of the mould could be connected to a pump that is capable of supplying or removing air from the mould. This pump system would be controlled by the pressure- and temperature-monitoring systems attached to the mould.

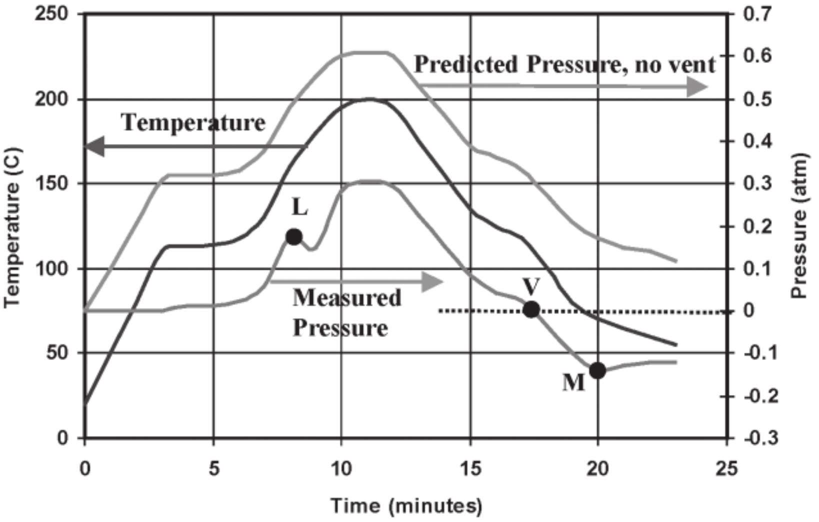

Fig. 10 Measured internal air temperature with measured and predicted mould pressure

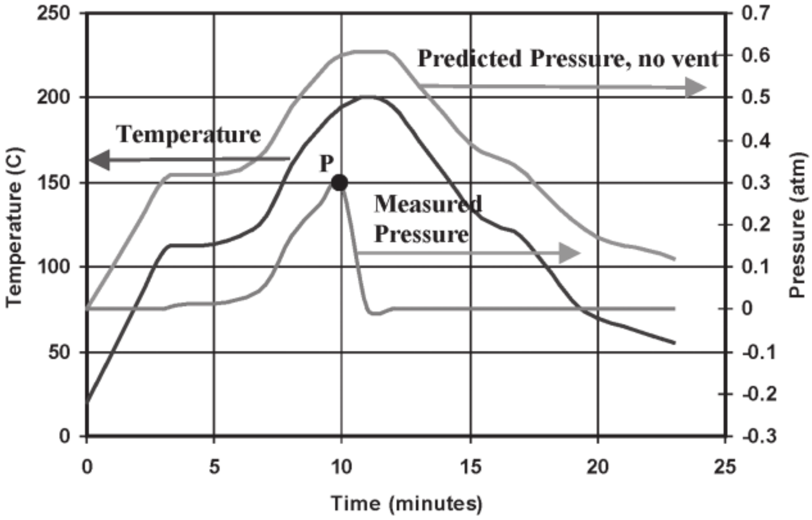

Fig. 11 Measured internal air temperature with measured mould pressure when a blowhole is formed

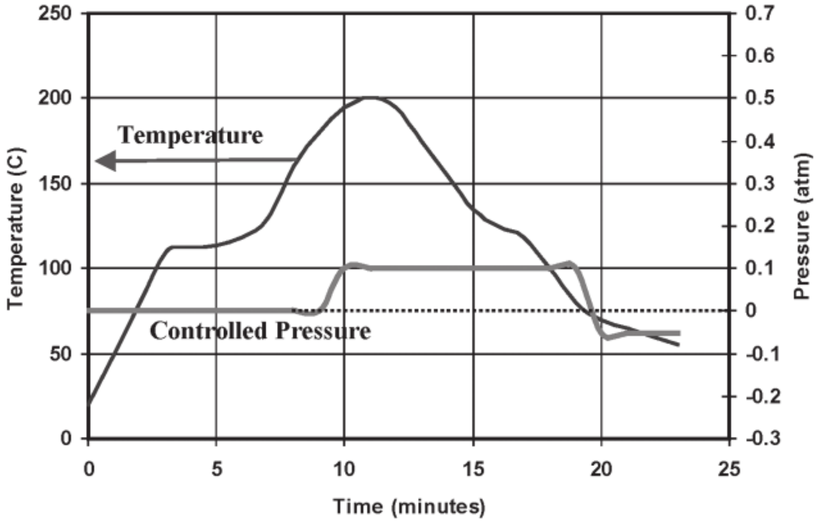

Fig. 12 Measured internal air temperature and ideal internal pressure profile achieved through active venting

Figure 12 is the suggested shape that the internal air pressure should have in order to create all the desirable effects referred to above. At a pre-set temperature, the pressure should be slightly positive to accelerate the removal of bubbles. This pressure should be maintained until a pre-set temperature during cooling, at which point the pressure should be slightly negative in order to facilitate demoulding. An active venting system would have a clearly defined role in achieving this type of pressure profile.

7 CONCLUSIONS

On the basis of this experimental study and a quantitative assessment of how gas bubbles are removed from the melt during the rotational moulding of plastics, the following conclusions may be drawn:

1. There are a number of mechanisms that operate simultaneously to remove bubbles and pinholes from the plastic melt during rotational moulding. It is difficult to isolate these due to the transient nature of the thermal processes that are taking place within the viscoelastic liquid. Migration effects are almost certainly negligible on the basis of both quantitative analysis and photographic recording in real time. Solubility into the melt of the gases within the bubbles is also relatively small, although the concentration gradient created close to the bubble is almost certainly the main driving force for the diffusion of the gases through the melt.
2. In normal rotational moulding, there is a natural sequence of events in which the gas diffuses out of the bubble, which reduces the size of the bubble and increases the pressure within it. This effectively increases the concentration gradient, which ensures

that the diffusion process continues. Thus, over a period of time the bubbles disappear.

3. If hydrostatic pressure is applied to the melt, then this provides a physical means of reducing the bubble size and accelerating the process. The levels of pressure needed are only a small fraction of an atmosphere. The most important points are:
   (a) that the hydrostatic pressure should be applied at the correct stage in the cycle and
   (b) that the level of pressure in the mould is known at all times.
4. The benefits of monitoring and controlling the pressure in the mould are:
   (a) that cycle times can be reduced,
   (b) that the properties of the moulded part are improved and
   (c) that greater consistency can be achieved in regard to tolerances.
5. It is essential that the rotational moulding industry addresses the challenge of continuously monitoring and controlling the pressure inside the rotating mould, to supplement the valuable process control information that is available by measuring the mould and internal mould air temperature. An important step in this process is to utilize active venting in which air is removed from, or added to, the space inside the mould. This would alleviate common moulding problems such as blowholes at the parting line and warpage of flat sections of moulded parts.

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