Shrinkage and Warpage of Rotationally Moulded Products

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1.0 Summary

Shrinkage and warpage of moulded plastic parts are caused by different effects but many of these are inter-related. It is important to understand the fundamental causes of these phenomena if one is to (a) avoid being mesmerised by apparently conflicting sets of observations and (b) identify solutions to problems occurring in particular circumstances. Shrinkage will always occur when a material cools from an elevated temperature. The extent of the shrinkage will be affected by the cooling rate. If the cooling is slow then the shrinkage will be large. It is important to note therefore that the moulder can control the amount of shrinkage by controlling the rate of cooling of the plastic. It is possible to have shrinkage without warpage but if the shrinkage is not uniform in all directions then this can lead to warpage. Also, if the natural shrinkage of the material is restricted from happening, due to the shape of the part or the presence of inserts or the use of jigs, then this leads to residual stresses in the plastic. Apart from non-uniform shrinkage, warpage also has a number of other causes, such as unsymmetrical temperature differences across the thickness of the material and, in the case of rotational moulding, unbalanced pressure effects. This paper discusses the relative magnitudes of these various factors in the context of rotational moulding and presents results from an extensive experimental study of warpage and shrinkage in rotationally moulded plastic parts.

2.0 Warpage

2.1 Temperature Gradient Effects: As indicated above, if the shrinkage in a plastic part is not the same in all directions then it will warp. This is often the case in large rectangular flat panels. However, in the context of rotational moulding, there are two other factors that contribute to warpage. Firstly, the unsymmetrical cooling in rotational moulding causes a temperature gradient across the plastic. The effect that this has is easily demonstrated by considering a piece of molten plastic being dropped on to a cold metal surface. The common observation from doing this is that the plastic curls upwards as it cools. The reason is that the lower surface of the plastic cools very rapidly when it touches the cold metal surface. The fast cooling results in low crystallinity and low shrinkage in this bottom layer. This frozen layer acts as an insulator and the upper layer cools much more slowly. It will have a higher degree of crystallinity and shrinkage and it tries to pull extra material from the bottom layer, causing it to curl upwards. As an aside, if the plastic is forced to be flat then this will set up residual stresses in the plastic.

The analogy of molten plastic cooling on a metal surface is exactly what happens in rotational moulding and therefore there is an inevitable tendency for the plastic to curl away from the mould. The only way to cure this problem is to cool the inside and outside surfaces of the plastic at the same rates. If this can be done then there will be no tendency for the plastic part to warp in the short term or the long term. Two points are important to note here. Firstly there is a misconception in rotational moulding that it is the rate of cooling that causes warpage ie "rapid cooling leads to warpage". This is not the case. It is the temperature difference across the plastic that causes the warpage. If this difference could be kept at zero, then very rapid cooling is possible without warpage occurring. A second point to note is that in some cases the warpage may not occur immediately at the time of moulding – perhaps due to the shape of the part. However, over a period of time, the residual stresses in the plastic part will lead to warpage, particularly if the part is subjected to elevated temperatures. If there is a symmetrical temperature difference across the wall of the plastic during cooling then there will be no long term distortion or warpage of the part, even if it is subjected to high temperatures. As a final practical point, it is important to note that it is very difficult to cool the outside and inside surfaces at the same rates. This is because the outside surface is cooled by convection because it is in contact with the metal mould. The inner surface can only be cooled by convection through the use of a cooled gas. This convective cooling is inherently slower and it would require precise monitoring and process control to cool the outside and inside surfaces at the same rate.

2.2 Pressure Gradient Effects: In rotational moulding, warpage is also caused by poor mould sealing at the parting line of the mould. During heating, air is forced out of the mould to maintain atmospheric pressure inside the mould as the inner air space temperature rises. As this inner air cools in the second half of the cycle, all of the expelled air must have time to re-enter the mould. If this is not possible, perhaps because cooling was too rapid or the vent tube is restricted, then the pressure inside the mould will drop below atmospheric pressure. If the mould is perfectly sealed this is not a problem because any pressure inside the mould should be sufficient to keep the plastic against the mould wall. However, if the mould is not sealed at the parting line then the pressure difference from the outside to the inside of the plastic is experienced by the wall of the plastic part and this unbalanced force causes warpage. It is interesting to observe that quite often this warpage will be in the opposite direction to that caused by the temperature gradient. It is also important to note that the shape of the part will dictate whether or not the part warps immediately at the moulding stage. For example, if plastic gets trapped at the mould parting line then the warpage that should occur cannot happen immediately but may be exposed later due to the residual stresses set up in the material.

3.0 Shrinkage

A major contributor to shrinkage is the close packing of the molecular structure of the plastic as it crystallises. This close packing into spherulites takes time and it occurs to the greatest extent when the material is cooled slowly. As a consequence, slow cooling causes large shrinkage. Conversely, fast cooling will result in a lesser amount of shrinkage. The moulder can therefore exercise some control over the amount of shrinkage that occurs. The obvious way to do this is through the judicious use of air and water cooling. However, it is also important to recognise that the plastic will cool faster when it is in the mould and in contact with the metal mould. The point at which the plastic separates from the mould often occurs randomly and this can lead to a variation in shrinkage from part to part even though they have been moulded under apparently identical conditions. The best way to ensure that the plastic releases from

the mould at a consistent point in the cycle is to utilise a small amount of pressure in the mould. If an early release coating or release agent is used then the plastic will attempt to separate from the mould very early. This is generally not desirable because it will result in large shrinkage and relatively low impact strength. A small amount of pressure inside the mould will prevent the early separation of the plastic from the mould and when the pressure is released the plastic will pull away from the mould wall at a consistent point in the cycle. It is also important to note that contrary to the practice adopted by most moulders it is better to control the cycle on temperature rather than time. This will assist with the production of parts with consistent shrinkage.
It should be noted from the previous sections that the shrinkage is controlled by the rate of cooling whereas the warpage is influenced by the magnitude of the temperature difference across the wall of the plastic.

4.0 Experimental Results

A 3 year experimental and analytical investigation of the shrinkage and warpage that occurs during rotational moulding has yielded some very useful results. It was found that the most important processing variables are the shot weight (or wall thickness of the moulded part), the peak internal air temperature inside the mould, the cooling rate and the temperature at which the part separates from the mould. In generic terms, these variables could probably be rationalised into other parameters that are of more fundamental relevance. However, these are the practical variables that are under the control of the moulder.

The general effects of some of these processing variables are illustrated in Figs 1-3.

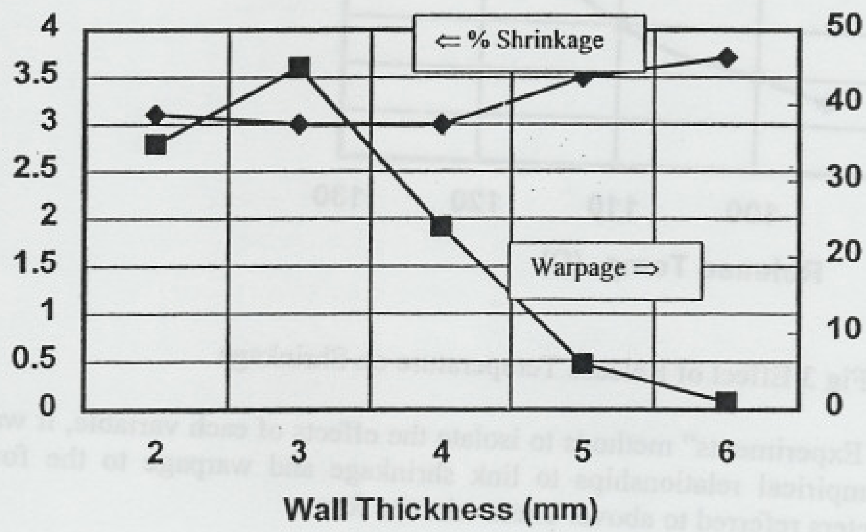

Fig 1 Effect of Part Wall Thickness on Warpage and Shrinkage

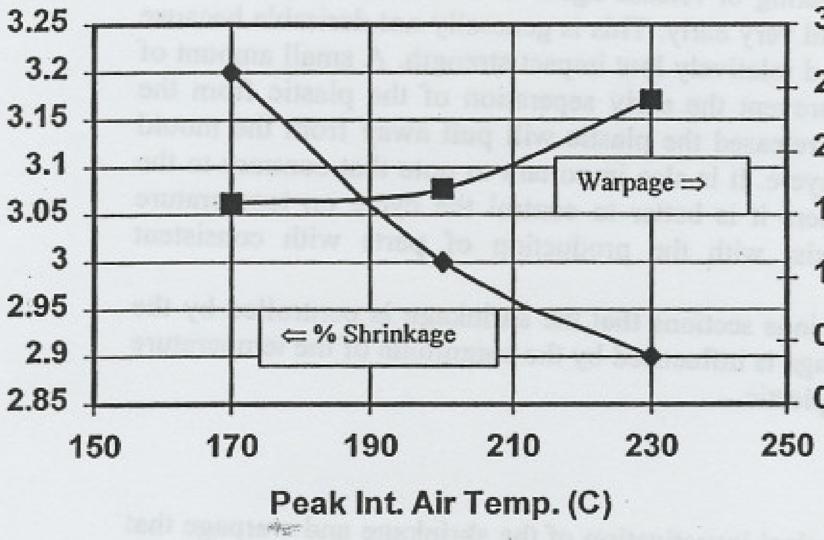

Fig 2 Effect of Peak Internal Air Temperature on Warpage and Shrinkage

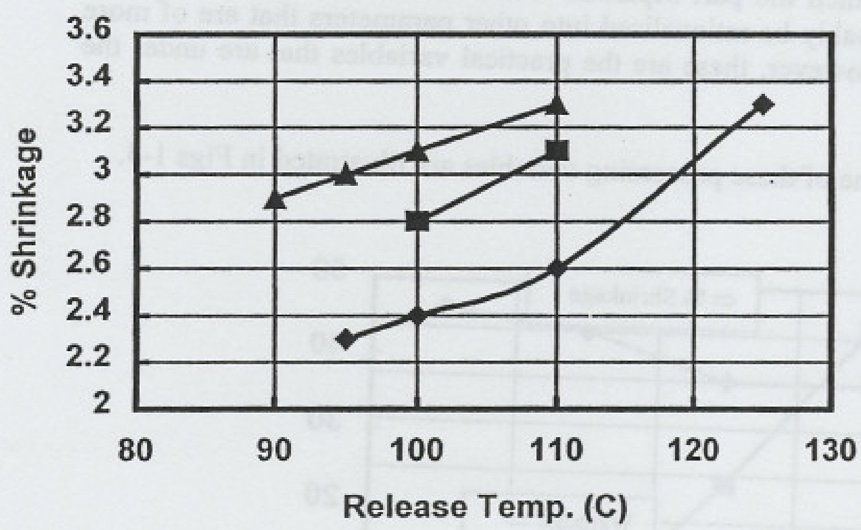

Fig 3 Effect of Release Temperature on Shrinkage

Using "Design of Experiments" methods to isolate the effects of each variable, it was possible to get empirical relationships to link shrinkage and warpage to the four processing parameters referred to above. These take the form:

$$\text{Shrinkage} = -0.139 + 0.000255A + 0.00028B - 0.0282C + 0.0303D + 0.121ABC$$

$$\text{Warpage} = 3.3 + 0.7AB - 1.8BC - 2.39\,AC - 1.91\,ABC - 0.00049A + 0.0857B + 0.154C - 0.166D$$

Where A = shot weight (g)

B = peak internal air temperature (^oC)

C = cooling rate (^oC/min)
D = release temperature (^oC)

5.0 Observations

From the experimental work carried out here the following observations were made.

(1) The geometry of the part has a major effect on shrinkage and warpage.
(2) Thicker parts tend to shrink more than thin parts.
(3) If the part is free to shrink, then slow cooling causes greater shrinkage. However, if the part is not free to shrink after it releases from the mould, then slow cooling causes lower shrinkage than fast cooling.
(4) If there is a tendency to high shrinkage in the material then the variability in shrinkage is high.
(5) The mould release agent has a significant effect on shrinkage and warpage. The temperature at which the plastic releases from the mould must be controlled to get consistent quality parts.
(6) Venting affects the dimensions of the moulded parts because it influences the pressure in the mould.
(7) The use of pigments affects the levels of shrinkage and warpage by changing the morphology of the moulded part.