5 Design for Functionality

5.1 Introduction

A moulded plastic part must satisfy the customer’s requirements in terms of functionality, longevity, aesthetics and economics. In all the moulding methods for plastics, the interrelationships between moulding conditions, mechanical properties and part quality are very important. This chapter focuses on the mechanical aspects of the performance of rotationally moulded parts. It also considers other factors that are relevant to the quality of the moulded part, such as the wall thickness distribution of the plastic, the ways in which roto moulded parts can be made stiffer, and the shrinkage, warpage and residual stress in the moulded part. Decoration technologies, such as in-mould graphics and painting, are also important ways of improving part quality, and so these are considered towards the end of this Chapter.

It is apparent from the preceding chapters that rotational moulding has characteristics that make it uniquely different from any other moulding methods. For example, to make changes to the wall thickness distribution in the end product it is not necessary to make changes to the mould – this can be achieved by changing the moulding conditions. Also, in rotational moulding it is possible to change the cooling rate, either deliberately or unintentionally, by quite significant amounts. Such changes can make major differences to the mechanical properties and the tolerances in the end product. In particular, the shrinkage of plastic mouldings is very sensitive to the rate at which they are cooled from the melt state to the solid state.

It is important that moulders understand the extent to which they can control the quality of the end-product by making changes during the moulding cycle. This will ensure that customer requirements can be met and will enable consistent quality parts to be produced under attractive economic conditions.
5.2 Preliminary Design Considerations

General considerations for designing rotomoulded parts include:

- Material.
- Number of parts.
- Size.
- Part complexity.
- Wall thickness.
- Tolerances and shrinkage.
- Warpage.
- Residual stress.
- Stiffening of parts.
- Double walled parts.
- Corner radii.
- Draft angles.
- Surface texture.
- Inserts.
- Graphics and surface decoration.

5.3 Material

As discussed in Chapter 3, rotomoulding has a limited number of materials available to the designer. The most commonly rotomoulded material is polyethylene (PE), but Nylon, polycarbonate (PC) and polyvinyl chloride (PVC) are also used (see Figure 5.1). The choice is usually dependent on the characteristics sought in the moulded part - strength requirements, rigidity, operating temperature, chemical resistance, colour and ultraviolet light requirements.
It should be recognised that if close process control can be applied during moulding, then a greater range of plastics can be rotomoulded. In general, polyethylene offers a large processing window – that is, a broad range of combinations of processing variables can be used to produce an acceptable moulded part – and so it is the most favoured material for rotomoulding. Other plastics have a much smaller processing window and so close control over processing variables is needed in order to achieve an acceptable moulded part.

Thermosetting plastics, and crosslinkable plastics, can be rotomoulded commercially although they are less commonly used.

**Figure 5.1** PVC medical face masks. Reproduced with permission from Rotoplastics Corporation

### 5.4 Number of Parts

The rotomoulding process tends to be most suited to small runs (50–5,000 units) but can be justified for up to 75,000 units per year. Higher volumes can be achieved particularly through the use of multiple tools as illustrated in **Figure 5.2**.

**Figure 5.2** Multiple cavity spider with 15 tools. Reproduced with permission from Maus GmbH
5.5 Size of Moulds

Rotomoulding is typically associated with large parts but there is a wide range of possible sizes. Figure 5.3 illustrates a large street sculpture part being demoulded whilst Figure 5.4 shows an open frame with a range of different sizes of moulds.

![Figure 5.3 Large street furniture part. Reproduced with permission from Persico SpA](image)

It is very common to have a range of different moulds on one machine arm. Figure 5.5 shows preparation to mount different sized moulds on a plate. Using the cardboard cut-out of the machine mounting plate, the moulder can move and position the moulds accordingly, ensuring adequate space between each tool to promote uniform heating and cooling. Generally it is good practice to mount differing moulds of a similar size on the same spider where the parts result in the same polyethylene wall thickness. This is called ‘balancing’ the moulds.
5.6 Part Complexity

A major advantage of rotomoulding is that very complex parts can be moulded in a single operation. Figure 5.6 shows a cross-section of a floor cleaning unit made up of a number of rotomoulded parts.

Normally the parts produced by rotomoulding are hollow but machining and finishing operations allow all types of geometries to be produced. Figure 5.7 shows a typical drilling operation on a rotomoulded PE part. Computer numerically controlled (CNC) machines facilitate quite sophisticated finishing operations to be carried out on rotomoulded parts.
Figure 5.7 Operator finishing a part. Reproduced with permission from Dutchland Plastics

Figure 5.8 shows on the left, a fire engine driver’s console manufactured from metal parts and vacuum formed acrylonitrile-butadiene-styrene. The right hand picture shows it replaced with a complex rotomoulded parts. Many rotomoulders are taking advantage of the opportunities to add value to the basic rotomoulded part by attaching metal components, fittings, gauges, and so on, so that the customer can install the part directly onto the intended location e.g., part of an automotive vehicle. This approach not only increases the value of the rotomoulded part but it provides the rotomoulder with the opportunity to deal with issues such as tolerances, shrinkage, warpage, and so on, rather than have the rotomouldings rejected by the end user because they do not conform to the agreed specifications.

Figure 5.8 Fabricated old part and rotomoulded new part. Reproduced with permission from Dutchland Plastics

The unique and complex design capabilities of rotomoulding can also be seen in Figure 5.9 which shows an old metal auger assembly (on top) converted to rotomoulding (on bottom).
5.7 Wall Thickness Distribution

Rotational moulding is a single-surface moulding process. In this way it is similar to thermoforming and blow moulding. This means that the mould can only affect the quality of one (the outer) surface of the moulded part. The free (inner) surface cannot have a controllable texture and the thickness of the plastic part cannot be controlled at all points as closely as if it was formed between two metal surfaces in, say, an injection mould. As a result, the wall thickness tolerance in rotational moulding is never as good as in two-surface processes such as extrusion and injection moulding.

On the positive side, the general thickness of a rotomoulded part can be increased or decreased by altering the amount of material placed in the mould. It is not necessary to make expensive changes to the mould as would be the case for injection moulding or extrusion. Another advantage of rotational moulding is that the wall thickness distribution of rotomoulded parts can be controlled relatively easily by changing the speeds of rotation of the mould about the two perpendicular axes. The ratio of these speeds has a major effect on wall thickness distribution.
Finally, in contrast to blow moulding and thermoforming, where the moulded parts have a tendency towards thinning in the corners, the fundamental nature of rotational moulding is such that these critical areas are usually thicker (see Figure 5.10).

**Figure 5.10** Cross-section showing wall thickness variations across moulding.
Reproduced with permission from Rototek Ltd

In rotational moulding, as well as blow moulding and thermoforming, it is common to specify a *minimum* wall thickness rather than a *nominal* wall thickness. For general purpose parts such as tanks and outdoor toys, the wall thickness variation in rotomoulded parts is typically ±20%. For certain products, such as medical facemasks and optical parts, a variation of ±10% can be achieved. As control systems in rotational moulding improve and there is a better understanding of what is happening during the process, the tolerances in rotationally moulded parts are improving.

A key to close tolerances is consistency in moulding conditions, particularly the point at which the plastic part separates from the mould wall. In normal rotomoulding, this release point can occur early or late during cooling, in a fairly random fashion from moulding to moulding. Part release depends on interactions of variables such as the amount of release agent on the mould, the cooling rate, the smoothness of the rotation, and so on. If the plastic part separates from the mould wall, then the air gap between the plastic and the mould means that control of the cooling rate of the plastic, via the mould temperature, has been lost. This leads to inconsistencies from part to part, and as the release does not occur equally at all regions of the moulded part, there will be different shrinkage in different areas of the moulding. This leads to warpage.

In modern control systems for rotational moulding, steps can be taken to keep the plastic against the mould wall until a consistent point in the cycle. One way to achieve this is to ensure that there is a slight positive pressure inside the moulding, up until the desired release point. This allows closer tolerances, and less warpage, to be achieved.
Table 5.1 shows typical wall thickness ranges for rotationally moulded plastics. Note that there are always exceptions to the values quoted, depending on the geometry of the part, the skills of the machine operator and the controls available on the moulding machine.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Minimum wall thickness range (mm)</th>
<th>Typical wall thickness (mm)</th>
<th>Maximum wall thickness (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LLDPE</td>
<td>0.5</td>
<td>1.5–25</td>
<td>75</td>
</tr>
<tr>
<td>High-density polyethylene</td>
<td>0.75</td>
<td>1.5–25</td>
<td>50</td>
</tr>
<tr>
<td>PVC</td>
<td>0.2</td>
<td>1.5–10</td>
<td>10</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>1.5</td>
<td>2.5–20</td>
<td>40</td>
</tr>
<tr>
<td>PC</td>
<td>1.25</td>
<td>1.5–10</td>
<td>10</td>
</tr>
<tr>
<td>EVA</td>
<td>0.5</td>
<td>1.5–20</td>
<td>20</td>
</tr>
<tr>
<td>PP</td>
<td>0.5</td>
<td>1.5–25</td>
<td>25</td>
</tr>
</tbody>
</table>

LLDPE: Linear low-density polyethylene  
EVA: Ethylene-vinyl acetate  
PP: Polypropylene

Although the rotational speeds, and the speed ratio, are usually fixed during rotational moulding, it is only in the second quarter of the cycle that their values are important. In the initial stage of the cycle, when the mould is not hot enough for the powder to stick to it, the rotation of the mould only serves to give good mixing of the powder and more uniform heat transfer to it from the mould. If there is a graphic on the inside of the mould, it might well be desirable to have slower rotational speeds during this phase of the cycle. Indeed it might be possible to have a speed ratio that keeps the powder away from the graphic to avoid dragging it off the mould.

On a rotomoulding machine, the mould will tend to get hotter when it is away from the powder. Therefore it is important to remember that the wall thickness of the part does not get thicker just by keeping it in contact with the powder pool for longer periods. It is an important combination of having the mould away from the powder pool to get hot and bringing it into contact with the powder pool to pick up powder.
The important message is that the wall thickness distribution in the moulded part is dictated by the rotational speeds and the speed ratio. But, as indicated earlier, their values are only important during the second quarter of the cycle when the plastic powder becomes tacky. This is the region A-B on the mould internal air temperature graph (see Figure 3.19, Section 3.10). During this period, which can be short if the wall thickness of the part is thin, it is very important to have all relevant parts of the mould surface coming into contact with the powder pool on a regular basis. Hence the rotational speeds and speed ratio are critical during this period. Also, if speed reversals are to be used to give the desired thickness distribution, then it is during this phase of the cycle that they will have most benefit. As there is very little melt flow in rotational moulding, the speeds and speed ratio during the rest of the cycle are not so critical. The plastic melt will stay in place against the mould so long as there is some mould rotation to stop sagging of the melt under its own weight. In rock and roll shuttle machines it is common to stop the rocking action, but maintain the rotation, when the mould comes into the cooling station.

An important practical point in regard to rotational speeds is that it is best not to have the speed ratio set as a whole number. If the speed ratio is set at exactly 4:1, for example, then the powder gets locked into a regular tracking path over the surface of the mould. This is not as good as having a speed ratio of 4.1:1 or 3.9:1, because these non-integer ratios cause multiple tracking paths over the surface of the mould. This will result in a better wall thickness distribution.

The other factors that affect the wall thickness distribution of the plastic are the uniformity of heat transfer to the mould and the uniformity of the mould wall thickness. The powder will adhere preferentially to the hottest parts of the mould. Thus, if the mould wall is thin in some areas, or if extra heat is directed to some surfaces of the mould, then the wall thickness of the moulded part will be greater in these regions. Problems can also occur if hot air cannot circulate freely into deep recesses of the mould. In such cases it may be necessary to use air movers to direct extra hot air into these inaccessible regions.

The converse, of course, is that it is possible to vary the wall thickness distribution in a controlled manner by shielding some areas of the mould surface. If they are kept cooler then there will be less material build-up in these areas (see Figure 5.11). It is also possible to get extra thickness in some critical areas by directing extra heat to these regions of the mould.
The overall message is that the moulder has a lot of control over the wall thickness of the moulded part mainly by controlling the speeds and speed ratio, but also by controlling the heat transfer to the surface of the mould. This is a major advantage in rotational moulding – the thickness of the part can be adjusted without making expensive changes to the mould. It is also crucial to recognise that the thickness distribution is decided during the second quarter of the cycle. Making changes to the moulding conditions during other parts of the cycle will have little effect on the wall thickness distribution.

5.8 Tolerances and Shrinkage

Plastics, like all materials, shrink (i.e., get smaller) when they cool. Crystalline polymers such as PE, PP and Nylon exhibit up to five times the shrinkage of amorphous polymers such as PC. If the polymer is unconstrained or allowed to shrink without restriction, shrinkage is uniform in all directions. As a result, the moulded part shrinks essentially uniformly in surface area and thickness. The exceptions are when the part is constrained by the mould shape. Male portions of the mould, such as ribs, bosses and gussets, or the presence of inserts, will restrict the natural shrinkage of the material. This can lead to other problems because differential shrinkage between unconstrained and constrained portions of the part can cause warpage, part distortion and residual stresses. Differential shrinkage can also occur if there are different cooling rates in different regions of the mould.
5.8.1 Shrinkage Guidelines

Plastics increase in density and therefore decrease in volume as they cool. Table 5.2 gives typical linear shrinkage values for the major rotationally moulded plastics. It should be noted that not only does the plastic change in shape when it shrinks, but its mechanical properties are affected. Slow cooling will cause greater shrinkage, higher density, higher modulus (stiffness) and greater strength but will result in lower toughness. Fast cooling will produce the opposite effects. Therefore, during rotational moulding it is possible to have different shrinkage in different areas of the moulding, or different shrinkage through the wall thickness, due to different cooling rates in different areas. This will cause different properties in different regions of the moulded part.

<table>
<thead>
<tr>
<th>Polymer</th>
<th>Shrinkage range (%)</th>
<th>Recommended (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear-low density polyethylene</td>
<td>1.6–3.0</td>
<td>3.0</td>
</tr>
<tr>
<td>12</td>
<td>3.0–3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>HDPE</td>
<td>1.5–2.2</td>
<td>2.2</td>
</tr>
<tr>
<td>PVC</td>
<td>0.8–2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>PC</td>
<td>0.6–0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Nylon 6</td>
<td>1.5–3.0</td>
<td>3.0</td>
</tr>
</tbody>
</table>

5.8.2 Control of Shrinkage

As discussed above, shrinkage occurs on a volume basis but moulders are most often concerned with the linear shrinkage of the dimensions of the moulded part. If the moulding is completely uniform and homogeneous in its structure then the linear shrinkage will be the same in all directions and will be approximately one third of the volumetric shrinkage.

Shrinkage cannot be avoided. It will always occur and so to prevent it becoming a problem it must be controlled. There are many factors that affect shrinkage – cooling rate, part wall thickness, molecular orientation, anisotropy, geometry of the part, material grade, reinforcements, filler/pigment content, inserts, oven temperature, release agents, mould material, and so on. It is important for the moulder to understand how the process parameters affect the dimensions of the end product.
The key to obtaining good quality parts is consistency in all aspects of the moulding operation. This section considers the factors that exert the greatest influence on shrinkage.

### 5.8.3 Effect of Release Point on Shrinkage

The relative amounts of the crystalline and amorphous phases in the plastic material have a dominant effect on the shrinkage that is observed. The effect of cooling rate on shrinkage that is observed by moulders is linked to:

- The *onset* of crystallisation, and

- The effect on the point at which the plastic moulding releases from the mould wall.

Fast cooling suppresses the onset of crystallisation and faster cooled parts release late from the mould. This late release from the mould, at a lower temperature, is normally associated with lower shrinkage. **Figure 5.12** shows experimental evidence to link shrinkage with release temperature for a selection of pigmented and natural grades of polyethylene.

The various lines in **Figure 5.12** relate to the same base resin with different types of pigment. This shows the importance that pigments can have on the shrinkage of rotationally moulded parts. Some pigments act as nucleating agents – these promote the onset of crystallisation in the plastic and this increases the amount of shrinkage that occurs.

When the plastic remains in contact with the metal mould, not only does it cool faster (which is associated with less crystallinity and lower shrinkage) but the plastic part is prevented from shrinking as much as it would like, due to frictional contact with the mould wall. It is common to get differences in shrinkage in the region of 0.5-1% depending on the point at which the moulding releases from the mould wall.

One of the most important factors in connection to the release point is consistency. It will be affected particularly by the nature of the release agent, as well as the uniformity and regularity of its application. If the effectiveness of the release agent is deteriorating over a period of time then the time at which the plastic part releases from the mould will change, with consequent variations in shrinkage. Also, if the application of the release agent is patchy, then the part will release in some areas and will progressively peel away from the mould causing variations in shrinkage across the part. This will lead to warpage.
Figure 5.12 Effect of release temperature on shrinkage of rotationally moulded polyethylene with different types of pigment

A very effective means of controlling the release point is to use an ‘early release’ coating on the mould and then arrange for some positive pressure to be applied inside the mould during the cooling phase. When this pressure is released, preferably at a consistent temperature rather than time, then it will be possible to maintain the level of shrinkage in the parts within close tolerances.

5.8.4 Other Factors Affecting Shrinkage

In a rotationally moulded polyethylene article, the typical shrinkages that are observed are between 3-4%. There are likely to be both small-scale (local) shrinkage effects and large-scale (global) effects.

The geometry of the part and the use of constraints (or anchor points) such as inserts will affect the shrinkage that is observed in different parts of a moulding. The designer/moulder must allow for the fact that the shrinkage will cause the position of inserts to move. If the moulded part is immediately joined to another part, so that movement
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(shrinkage) of the insert is prevented, then this will set up residual stresses in the part. The presence of these stresses may not be immediately apparent but they may be exposed later when the part is in service – premature fracture or stress cracking may occur. Shrinkage will continue for a time after moulding but most of the dimensional change occurs within the first 24 hours after moulding.

Other factors that influence the shrinkage are the wall thickness of the moulded part, the peak internal air temperature inside the mould, the cooling rate, the basic nature of the resin/additive package and the temperature at which the part releases from the mould. To produce parts to close tolerances, all of the process parameters need to be carefully controlled. Thicker products shrink more than thinner parts because they cool more slowly. And for parts where the shrinkage is high then the variability also tends to be high. This variability in shrinkage in a moulded part will lead to warpage. Thus, if there are thick sections and thin sections in the moulding there is a greater likelihood that it will warp. This can be difficult to avoid in rotomoulding as there is a natural tendency to have thicker regions in corners of a moulded part.

The effectiveness of the venting has also been shown to have an influence on shrinkage in that it can affect the release of the part from the mould wall. If the vent is not operating correctly then the pressure inside the mould can be positive (i.e., above atmospheric pressure) or, as is more likely, below atmospheric pressure during the cooling phase. In the former case, the pressure inside the part will keep it against the mould wall, whereas in the latter case the slight vacuum will tend to pull the plastic part away from the mould more readily.

Other important process parameters are the shot weight, the peak internal air temperature inside the mould, the cooling rate and the type of pigment used. It is important to note that it is the cooling rate that affects shrinkage but this is not the prime cause of warpage – the temperature gradient across the plastic affects the warpage. Warpage is linked to shrinkage in that differential contraction in different parts of a moulding, or in different directions across a moulding, will cause warpage. If shrinkage is prevented from occurring then this will lead to residual stresses being set up. It should be recognised also that this could occur if jigs are used after moulding, to constrain shrinkage or prevent warpage. Any action that prevents the plastic from taking up its natural shape will result in residual stresses in the moulded part.

5.9 Warpage

If a moulded plastic part bends or changes shape, it is because there are forces (stresses) acting on it. These forces need not be applied externally or be readily apparent. Quite often there are internal (residual) stresses set up as the structure of the material forms
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during the cooling part of the rotomoulding cycle. If a molten plastic is subjected to fast cooling on one side and slow cooling on the other side, there will be a difference in the structure across the thickness of the plastic when it becomes solid. The side that cools slowly will have a tendency to be more crystalline. This means that the molecular chains pack together more closely and the plastic will have a higher density in this region. The net effect is that the plastic is stronger and stiffer but it will be less tough in this region.

The side that cooled more quickly will be less crystalline because the material did not have time for the molecular chains to align themselves into a crystalline structure. In this region, the material will have a lower density, resulting in lower strength and stiffness but greater toughness. This non-uniformity of structure sets up stresses in the material. The crystalline region of the moulding tries to pull material from the less crystalline part. This leads to warpage and differential shrinkage.

In rotational moulding, the cooling rate is normally different across the thickness of the plastic. Therefore, there are stresses set up across the wall of the plastic and these can distort the plastic. This is what we observe as warpage. If the shape of the mould is such that the rotomoulded part is constrained from changing shape, then residual stresses will be set up in the part. The use of jigs to force the plastic into shape after it has been removed from the mould will also cause residual stresses in the end-product. The more uniform the part wall thickness becomes, the more uniform the shrinkage becomes. However, even for products with very uniform wall thicknesses, warpage can result. Warpage is a manifestation of the non-uniformity of shrinkage. The problem is particularly critical for parts with large flat surfaces. The edges of the parts are constrained by the mould corners while the centres of the flat surfaces pull away from the mould walls, causing a bowing or warpage. Table 5.3 gives industry-established standards for warpage of several polymers.

Table 5.3 Typical warpage values for rotationally moulded plastics

<table>
<thead>
<tr>
<th>Plastic</th>
<th>Commercial (%)</th>
<th>Precision (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>2.0</td>
<td>2.0</td>
</tr>
<tr>
<td>Nylon</td>
<td>0.5</td>
<td>0.3</td>
</tr>
<tr>
<td>PP</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>PVC plastisol</td>
<td>2.0</td>
<td>1.0</td>
</tr>
<tr>
<td>PC</td>
<td>0.5</td>
<td>0.3</td>
</tr>
</tbody>
</table>

While flat surfaces on plastic parts can be appealing from an aesthetic point of view, they are difficult to achieve with single-sided, low-pressure processes such as blow moulding, thermoforming and rotational moulding. It is good design practice with rotomoulded parts to use curvature effectively to conceal warpage. If a flat surface bends or warps it
is very noticeable, particularly if the surface has a high gloss finish. The human eye can
detect very small changes in flatness. On the other hand, if a surface is designed to be
curved and it changes shape slightly, then this is not noticeable. Also, as very smooth or
glossy surfaces accentuate distortion, a certain degree of warpage can be accommodated
without causing a visual imperfection if the surface texture is engraved, etched, or speckled.

5.9.1 Control of Warpage

It is often said that the cause of warpage is fast cooling and moulders will relate this
observation to their experience. There is also ample scientific evidence to support this.

**Figure 5.13** Warpage as a function of cooling method and mould material.

![Warpage graph](image)

It is important to realise that the main factor causing warpage in rotationally moulded
parts is not the cooling rate, but the temperature difference across the part wall. If
the inside surface of the moulding could be cooled as quickly as the outside surface
then there would be no restriction on the cooling rates that could be used without
causing warpage. If the cooling rates were balanced across the wall thickness of the
part (see **Figure 5.14**) then the structure of the wall thickness of the moulded part
would be symmetrical about its centre line and there would be no tendency for it to
bend (warp) in any direction. The beauty of such balanced cooling is that not only
is there no tendency for the part to distort during moulding or demoulding, but in
service it will retain its shape because there are no unbalanced stresses in the material.

In practice, it is difficult to achieve equal cooling rates on the outer and inner surfaces
of a moulding because (a) there are likely to be thickness variations throughout
the rotomoulded part and (b) the heat transfer rate by conduction from the plastic
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to the metal mould is greater than the heat transfer rate by convection from the plastic to the gas inside the mould. The former situation means that warpage can be affected very significantly by anything that affects wall thickness distribution – such as speeds and speed ratios, shielding, etc. The latter effect caused by the heat transfer mechanism can be improved if a cooling gas or liquid is circulated inside the mould.

From the earlier comment about the lower efficiency of convection inside the mould, very cold gas needs to be continuously fed inside the mould to create anything like the cooling effect that can be achieved on the outside.

In an effort to reduce cycle times, and introduce better process control, an increasing trend in rotomoulding is to use internal cooling such as refrigerated air or water spray inside the mould. In the latter case the water spray turns to vapour inside the mould and exhausts through the vent. It is easier to introduce the water spray (or air) in moulds that have a large volume of space inside the moulding. If there is only a narrow space inside the mould then the introduction of the water spray (or jets of cold air) may distort the molten plastic on the inside surface of the mould.

Although warpage is primarily controlled by the cooling conditions during rotational moulding, it will be affected by a number of other factors. For example, the type of mould release can exert an effect because the cooling rate on the outer surface of the part will be greater when it is in contact with the metal mould. As the release agent can control the point at which release occurs, it can therefore affect the magnitude of the warpage. The use of internal pressure during cooling can provide an opportunity to control this by keeping the plastic in contact with the mould wall for longer, and perhaps more importantly, providing an opportunity to ensure consistency in the point at which the plastic part separates from the mould wall.

![Diagram showing effect of internal cooling on the structure of a rotationally moulded plastic part](image)

**Figure 5.14** Effect of internal cooling on the structure of a rotationally moulded plastic part
The oven temperature and/or time in the oven can also be a factor in regard to warpage because if the cooling conditions are kept constant then starting from a higher mould temperature will result in a different cooling experience for the plastic part. The temperature variation across the part wall is most important when the plastic starts to solidify. Thus when the mould temperature is above about 140°C (284°F) the cooling rate could in theory be faster. In practice, once fast cooling is used, a thermal momentum is built up and it is difficult to slow the cooling rate back to the desired levels again in the critical period.

The density of the plastic will also be important but the effect is complex. Higher density parts will have a greater tendency to crystallise and initiate higher levels of structural variation (stress) across the mould wall. The higher density materials will have a higher modulus and therefore a greater ability to resist this applied stress. The thickness of the part will also be important because not only does it contribute to the greater temperature difference across the mould wall, but it affects the stiffness of the part and thus its ability to resist the applied stresses.

The use of pigments can also affect, in different ways, the manner in which the plastic crystallises (solidifies) so it is quite common to find that warpage effects are much greater with some colours than with others.

5.10 Residual Stress

A large proportion of all failures of moulded plastic parts arise as a result of moulded-in stress. Although it is often stated that an advantage of rotomoulding is that the moulded parts have no residual stress, in reality what is meant is that the residual stresses are small relative to other competing moulding methods. Most rotationally moulded products do contain some residual stress, not as a result of stresses on the melt during forming but as a consequence of restricted shrinkage or restrained warpage during cooling. These hidden stresses within the material reduce the effective strength of the plastic and, more importantly, can lead to environmental stress cracking problems.

Designers of injection moulded parts are well aware of the problems of residual stresses – sometimes referred to as internal stresses. Thus they will try to avoid things like changes in thickness in the plastic part because they know that thick areas will cool more slowly than thin areas and the resulting differences in the structure/morphology of the plastic will set up stresses in the plastic. Injection moulded plastic parts that are well designed have uniform wall thicknesses everywhere, and structural features such as ribs are used to impart stiffness to the end product.
In the case of rotational moulding, the moulder as well as the mould designer, has control over wall thickness. As discussed earlier, the rotational speeds and speed ratio, the mould position relative to the axes of rotation and the heating uniformity will affect the thickness of the final part. Also, the cooling rate is relatively slow in rotational moulding and this encourages large shrinkage in the plastic. Restriction of this shrinkage, in whole or in part, will influence the level of residual stress in the plastic.

In general, residual stress in a moulded plastic part is caused if the plastic is forced to take up a shape that is not natural for it. Thus, during cooling, the plastic will want to shrink and if this shrinkage is restricted then residual stresses will be set up. This effect is illustrated in Figure 5.15. If there is differential shrinkage this will lead to warpage, and if the warpage is restrained by jigging, for example, then residual stresses will be set up in the plastic. This is illustrated in Figure 5.16.

The magnitude of the residual stress in a moulded plastic part will depend on many factors. If the primary cause of the residual stress is restricted shrinkage, then the level of moulded-in stress can be linked directly to the characteristic stress-strain graph for the plastic. For example, if the plastic tries to shrink by 1% but is not allowed to do this, due to the presence of inserts or because of the shape of the mould, then the stress set up in the plastic will be 0.01 (i.e., 1%) multiplied by the modulus of the plastic. Alternatively the value of the stress could be read from the stress-strain graph, as shown in Figure 5.17, if it is available. If the restricted strain (shrinkage) is greater, then the residual stress will be proportionally higher, as shown in Figure 5.17.
It should be noted that it follows from the previous argument that the level of residual stress will be related to the cooling rate. Fast cooling results in lower shrinkage and hence lower residual stress. Conversely, slow cooling will tend to produce high levels of crystallinity, high modulus, high shrinkage and thus high levels of residual stress.
5.10.1 Short-term Effects of Residual Stresses

The typical effects of residual stress in a plastic are to reduce the service strength and impact resistance of the plastic. This can be illustrated in simplistic terms as follows. If the plastic normally has a strength of, say, 110 MN/m² then if there was no residual stress in the moulded plastic, one could apply this stress before failure would occur. If the moulded plastic has a residual stress of 30 MN/m², as illustrated in Figure 5.18, then in service it would only be possible to apply an external stress of 80 MN/m² before the part would break. Therefore, as far as the user is concerned, the strength of the material has been reduced from 110 MN/m² to 80 MN/m². A similar argument can be applied to impact strength, so that residual stresses are highly detrimental to the performance of the plastic.

![Figure 5.18 Effect of residual stress on the strength of a plastic](image)

5.10.2 Long-term Effects of Residual Stresses

The difficulty with residual stresses is that they are a hidden danger in the plastic part. Immediately after moulding, the part may pass all quality control tests in terms of appearance, dimensions, physical properties, and so, but as time progresses, the effects of the hidden internal stresses become exposed and the part fails in service. It is important that the rotational moulder recognises the way that the processing
conditions affect the levels of stress in the moulded part, in order that the long-term, as well as the short-term, aspirations for the part are met.

The viscoelastic nature of plastics means that the levels of residual stress in a moulding decrease with time. This is good news but it is offset somewhat by the fact that the modulus of the plastic also decreases with time. This latter effect means that it gets easier for whatever stress is present in the plastic to deform it. Consequently, sometime after moulding, the residual stress can be such that it will cause the moulded part to deform and warp. This effect becomes worsened if the temperature of the plastic part is raised because this leads to a further decrease in modulus.

Probably the most severe effect of moulded-in stresses is environmental stress cracking (ESC). This usually refers specifically to a phenomenon observed in polyethylene. It is the tendency for polyethylene parts to fail prematurely in the presence of certain ‘active’ environments, such as detergents and oils. A characteristic feature of this type of failure is that it requires the presence of stress and a particular liquid to be present simultaneously. Remove either the stress or the liquid and the problem does not occur. Unfortunately, if there are residual stresses in a material, we will always have present at least one of the two factors needed to cause environmental stress cracking. The moulded part will therefore be much more susceptible to ESC if it comes into contact with the active liquid environment, even if no external stresses are applied.

5.10.3 Cures for Residual Stress Problems

The best approach to alleviating the levels of residual stresses in rotationally moulded parts is to remember that they are closely linked to shrinkage and warpage. Therefore, anything that relieves these problems will also reduce residual stress levels. Controlling the cooling rates is a particularly effective in this regard. Faster cooling will reduce the tendency for the part to shrink and so, if the part is restrained by inserts, or mould undercuts, the level of stress in these areas will be less. However, fast external cooling will lead to greater warpage if no attempt is made to balance it with faster internal cooling. Therefore, in general, the use of internal cooling is likely to reduce residual stress in rotationally moulded parts.

The effectiveness of the release agent will also influence residual stress levels. It has been shown that once the plastic releases from the mould, the cooling rate of the plastic is slower and this leads to larger shrinkage. At the very least, the point at which the plastic releases from the mould should be consistent to avoid random variation in residual stress levels from part to part. Exercising control over the release point may also be an effective way of modifying residual stress levels. Late release from the mould will cause lower levels of residual stress. It has been demonstrated that the best
way to monitor the release point is by recording the temperature of the mould and the temperature of the air inside the mould. Distinct changes in these temperatures can be seen when the plastic separates from the mould wall. Monitoring the pressure inside the mould will also assist with controlling the release point – the use of a small pressure inside the mould is a very effective way of achieving the desired effect, but may in itself result in higher levels of residual stress in the end product.

5.11 Stiffening of Parts

The dominant material in the rotational moulding industry is polyethylene. Due to the inherent low modulus of this material, designers and rotomoulders must use geometrical features such as corrugated sections and ‘kiss-off’ points to impart stiffness to rotomoulded parts. Figure 5.19 shows a typical design for rotomoulded corrugations.

![Minimum dimensions for hollow ribs](image)

**Figure 5.19** Cross-section showing dimensions of hollow ribs

A major advantage of rotational moulding is that ‘kiss-off’ features (see Figure 5.20) can be used to tie together the two walls of a double wall part. This adds very significantly to the stiffness to weight ratio of the moulded part. Another feature of rotomoulding is that foamed polyethylene can be used to fill the space between the two walls and this increases the stiffness to weight ratio by many orders of magnitude.

![Cross-section showing typical ‘kiss-off’](image)

**Figure 5.20** Cross-section showing typical ‘kiss-off’
5.12 Double Walled Parts

Narrow cavities are easily formed in rotomoulded parts, which facilitates double walls as illustrated in Figures 5.21 and 5.22. A constraint on the production of such parts is the ‘bulk density’ of the powder, which is approximately one-third that of solid moulded material. This means that a volume of at least three times the volume of the solid part is required inside the mould to accommodate the powder at the beginning of the cycle, and to facilitate some flow of the powder inside the mould.

Figure 5.21 Cross-section showing wall thickness variations across twin-wall moulding. Reproduced with permission from Rototek Ltd

Figure 5.22 Cross-section showing wall thickness variations across moulding. Reproduced with permission from Rototek Ltd
5.13 Corner Radii

A general design principle for rotomoulded parts is that corner radii should be as generous as possible. This not only reduces stress concentrations but it facilitates smooth flow of the powder over the surface of the mould and helps to create uniform wall thickness throughout the moulded part. Figure 5.23 demonstrates the types of effects that occur typically in rotomoulded parts. There is usually thickening at internal corners because the powder gathers in these regions, and there is thinning at external corners because the powder, and melt, falls or flows away from these regions.

![Figure 5.23 Wall thickness variations. Reproduced with permission from Rototek Ltd](image)

5.14 Draft Angles

It is possible to mould parts with zero draft but it is generally desirable to allow at least a small draft angle to facilitate extraction of the part from the mould. Generally a draft angle of 1-2 degrees is sufficient. It should be noted that internal features such as cores, where material shrinks onto the mould will also require a draft angle to be designed into them.

5.15 Surface Quality

Rotationally moulded parts are often characterised by bubbles (or ‘pin-holes’ on the surface and within the wall thickness of the moulded parts. The creation of the bubbles (pin holes) in rotomoulded parts depends on a wide range of factors – primarily the following:

- **Particle size**: The quality of the powder has an important influence on the formation of bubbles and pin-holes in rotomoulded parts. Small particles tend to trap small air
pockets (bubbles) and these will disappear from the melt more quickly. Conversely large particles trap larger pockets of gas and these will take longer to disappear.

- **Particle size distribution**: It is not known what is the perfect particle size distribution for rotational moulding but the companies that produce powders normally know what is a good distribution and what is a bad distribution. It is undesirable to have all the particles the same size as this causes inefficient packing of the powder particles. A ‘good’ distribution usually has particles ranging in size from about 100 µm to about 500 µm with an average of about 300 µm. Note that during rotational moulding the tumbling of the powder causes a sieving action with the result that the fine particles adhere first to the mould surface and the coarser particles migrate to the inner free surface of the moulding.

- **Particle shape**: As with particles size distribution, it is not known what the perfect particle shape is. Regularly shaped particles, such as spheres, are generally to be avoided as they do not pack together very densely. The main thing to avoid is particles that have excessive surface projections, such as ‘strings’ caused by melting during production of the particles. These surface projections cause poor powder flow and prevent the particles from packing together densely. The latter results in excessive bubble sizes which will take longer to disappear. As a consequence of the influence that powder quality has on bubbles it is important for the moulder to continually monitor the powder quality using simple procedures such the dry flow and bulk density tests (see Chapter 4).

- **Viscosity of plastic**: The moulder cannot exercise control over the viscosity of the plastic, except by increasing the temperature. Generally bubbles and pin-holes will disappear more easily when the shear viscosity of the melt is low. A low viscosity is reflected in a high melt flow index so the bubbles disappear more easily in higher melt index materials.

- **Surface tension at mould/plastic interface**: In order to make surface pin-holes disappear it is desirable to have the surface tension of the metal mould higher than the surface tension of the plastic melt. However, in this situation the moulded plastic tends to adhere to the mould and it is more difficult to get the part out of the mould. To alleviate this problem it is normal to use a release agent on the mould surface. The effect of the release agent is to reduce the surface tension of the metal mould surface and this will tend to make surface bubbles more likely. Therefore, a release agent should be used sparingly if surface pin-holes are to be minimised.

- **Elasticity of the plastic**: The moulder has no control over the elasticity of the melt – this is a parameter that can be varied by the material supplier. The moulder simply needs to be aware that different grades of a plastic, from the same or different supplier, may have different tendencies towards bubble formation and removal.
During a normal rotational moulding cycle the bubbles are removed on the basis of a combination of temperature and time. Using practice and experience the moulder adjusts the oven temperature and the time in the oven to achieve the best combination that will produce parts with the fewest number of bubbles on the surface or within the wall of the moulded part. A common test to assess the correct cycle is to take a thin slice from the thickness of the wall of the moulding and hold it up to the light. The ‘best’ cross-section is to have no bubbles towards the mould wall and a few small bubbles towards the inner, free surface. If there are no bubbles in the cross-section then it may be that the part has been over-heated and may have become embrittled. Hence, it is best to see a few small bubbles still remaining to have the reassurance that the plastic part has not been overheated.

As stated previously, it is prudent to measure the powder properties over a period of time to assess whether or not there are variations in powder quality that could be contributing to the creation of excessive bubbles in the melt.

It is also worthwhile to monitor the pressure inside the moulds because by controlling the pressure it is possible to make the bubbles disappear physically rather than relying on the oven time and temperature to remove the bubbles.

### 5.16 Surface Texture

The surface textures of rotomoulded parts can range from a mirror polish to rippled surfaces, and can be varied on the same part to provide very attractive aesthetic features. As with most moulding technologies, highly polished surfaces can be costly to produce and maintain. Figures 5.24 and 5.25 show examples of different mould finishes.

![Multiple different mould finishes](image_url)

**Figure 5.24** Multiple different mould finishes. Reproduced with permission from Maus GmbH
5.17 Graphics and Surface Decoration

As plastics can be brightly coloured by mixing a pigment with the plastic, rotationally moulded parts are normally used without further surface colouring (such as painting) or decoration. In certain cases, logos or instructions can be moulded in as raised or depressed portions of the part surface, again without further surface colouring or decoration. The nature of the plastic must be considered when the part dictates that further surface enhancement is necessary. Not all plastics lend themselves to painting. For example, solvent-based paints will adhere quite well to PVC, PC and polystyrene. On the other hand, polyolefins (including PE) are not naturally receptive to paints. If painting is necessary on materials such as LLDPE, PP and EVA, then chemical etching, flame treating or other special methods of surface activation are necessary prior to painting.

5.17.1 Painting

As discussed previously, it is difficult to paint PE unless the surface of the moulded part receives special treatment. If the moulded surface needs to be made receptive to paint then flame treatment can be very effective. Once this has been done, traditional spray painting techniques can be used (see Figures 5.26 and 5.27). In certain cases, a portion of the part may be silk-screened. This is a traditional process of forcing a special ink through an appropriately masked screen onto the prepared plastic surface. Although the process is restricted to surface areas of about 1 m², the technique allows extremely fine details to be transferred. It is also becoming more common for some rotomoulders to go to a lot of trouble to prepare the PE surface to be receptive to the types
of paints, and hard (high gloss) finishes that are common in the automotive industry. These techniques are becoming common in the rotomoulded furniture industry and the mouldings are of superb quality with a very high added value.

It should be noted that there are some new grades of PE that have been treated as a powder so as to make the moulded surface receptive to paint. These materials can be moulded in the normal way and then painted without the need for any special post-moulding surface treatment.

Figure 5.26 Paint sprayed onto moulded part. Reproduced with permission from Mold In Graphic Systems

Figure 5.27 Final flame treatment. Reproduced with permission from Mold In Graphic Systems
5.17.2 Hot Stamping

Hot stamping involves the use of a foil or film containing the appropriate printed, embossed or textured surface on one side and a thermally compatible polymer film on the other. It is placed between the plastic surface and a hot plate, which presses the film or foil against the plastic surface, fusing the two together. Hot stamping can be used to transfer very elegant decals, or to imprint the date and time of moulding and bar codes.

5.17.3 Adhesives

Adhesive-backed ‘decals’ can be used to decorate rotomoulded plastics. The most popular adhesive is a pressure-sensitive adhesive (or PSA). It is commonly activated by stripping off a carrier film. If the decal is to be permanent, the surface must be properly prepared so that the adhesive contacts as much of the plastic surface as possible and bonds chemically to it. In some instances, the decal may be semi-permanent, for example, for protective films or assembly instructions. There are PSA designed specifically for this application, but surface preparation of the polymer is critical to provide the desired adhesion.

5.17.4 In-mould Decoration

In-mould decoration has become very popular in the rotomoulding industry. The in-mould transfer consists of the decorative image applied to a film of the polymer type being rotationally moulded. The decoration is carefully placed and fixed at the appropriate location in the mould prior to powder filling (see Figure 5.28). During the heating stage of the rotomoulding cycle, the polymer in the film melts and powder sticks to it. When the cooled part is removed from the mould, the decoration is permanently embedded in the surface of the moulded part (see Figures 5.29 and 5.30). Care must be taken during the early stages of rotation to prevent the dry powder from scuffing or lifting the decoration off the mould surface.

Another in-mould decoration system available is Mold In Graphic Systems® Color-In System. This technique employs spray painting and enables multiple colours to be integrated into rotomoulded parts. Since this system embeds itself directly into the surface of the moulded plastic, the new custom design is permanent and resistant to attack by chemicals, solvents or extreme weather conditions.
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Figures 5.31-5.33 illustrate the use of Mold In Graphic Systems® Color-In System spray on graphics in rotomoulding.

Figure 5.28 Graphic applied to inside of mould prior to moulding. Reproduced with permission from Mold In Graphic Systems

Figure 5.29 Graphic in place following demoulding. Reproduced with permission from Mold In Graphic Systems
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Figure 5.30 Graphic on final moulded part. Reproduced with permission from Mold In Graphic Systems

Figure 5.31 In mould colour spray. Reproduced with permission from Mold In Graphic Systems

Figure 5.32 PE powder placed in mould. Reproduced with permission from Mold In Graphic Systems
5.17.5 Post Moulding Decoration

Transfers, similar to those described for in-mould use, have also been developed so that they can be applied to the plastic part after it has been moulded (see Figures 5.34 and 5.35). This can reduce scrap rates because in-mould transfers can get damaged, or may not properly adhere to the plastic, during moulding.

Examples of in-mould graphic parts are illustrated in Figure 5.36.
Figure 5.35 Flame treatment of moulding surface with graphic. Reproduced with permission from Mold In Graphic Systems

Figure 5.36 Examples of mold-in graphics. Reproduced with permission from Mold In Graphic Systems
5.18 Design of Foamed Sections

Foaming is a very valuable tool for the designer of rotomoulded parts. Section 4.9.9 describes in detail the many ways it is process in rotational moulding. Conventional ribs (common in injection moulded parts) are difficult to create by rotational moulding because the plastic powder does not flow easily into the recess needed to create the rib. Instead the same type of stiffening effect can be created using corrugations as shown in Figure 5.37. The recommended depth of the corrugations is about four times the material thickness and the width should be about five times the material thickness. This is to ensure a good balance of axial and transverse stiffness. Special stiffening features called ‘kiss-offs’ are very effective in rotational moulding (see Figure 5.38). These are created in double wall parts by conical features in the mould that cause the two walls of the part to be bonded together. The resulting moulding is very stiff and in some cases, such as in pallets, foaming is added to provide excellent stiffness to weight ratio.

![Figure 5.37 Typical dimensions of stiffening corrugations in rotationally moulded parts](image1)

![Figure 5.38 ‘Kiss-off’ stiffening features in rotationally moulded parts](image2)

The stiffness of a moulded part that is loaded in flexure (bending) is proportional to the product of the second moment of area (I), and the modulus (E), of the material.
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Designers of rotationally moulded parts must use shape very efficiently to increase the
I value because the modulus of polyethylene is relatively low, and it decreases with time.

For a solid wall rotationally moulded part, the second moment of area, $I$, is given by

$$I = \text{(width)} \times \text{(thickness)}^3/12$$

It may be seen from this equation and Figure 5.39 that a very effective way of
increasing $I$ is to increase the wall thickness of the moulded part. For example
doubling the thickness will give 8 times (i.e., $2^3$) greater stiffness. However, the weight
of the part, and hence its cost, is doubled and the cycle time will be significantly
increased.

![Figure 5.39 Factors used to calculate stiffness of solid rotomoulded part](image)

5.18.1 Solid/Foam Cross-sections

The advantage to be gained by adding a foam layer may not be immediately apparent
since the modulus of the foam is very much less than that of the solid plastic. In fact
the use of the foam is like adding a stiffening rib to the plastic. This is illustrated in
Figure 5.40.

![Figure 5.40 Illustration that foam effectively acts as a rib](image)
5.18.2 Solid/Foam/Solid Cross-sections

Even more impressive gains can be made if the cross-section of the rotomoulded part is enhanced with an inner solid layer (see Figure 5.41). Such sandwich sections are extremely efficient at resisting bending stresses and are very efficient in terms of the stiffness per unit weight that they provide. The skin thickness can be typically only about 1 mm thick to provide a very strong and stiff structural element.

![Figure 5.41](image)

**Figure 5.41** Foam effectively acts as a rib in sandwich cross-section